

**Ontario Geological Survey
Special Volume 1**

The Geology and Ore Deposits of the Sudbury Structure

Edited by

E.G. Pye, A.J. Naldrett, and P.E. Giblin

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Every possible effort is made to ensure the accuracy of the information contained in this volume but the Ministry of Natural Resources does not assume any liability for errors that may occur. Source references are included in the report and users may wish to verify critical information.

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A MESSAGE FROM
THE HONOURABLE ALAN W. POPE
ONTARIO MINISTER OF NATURAL RESOURCES

It is with considerable pride and pleasure that the Ministry of Natural Resources presents the first in its new Special Volume series, *The Geology and Ore Deposits of the Sudbury Structure*, a book that represents a landmark in geological studies of the Sudbury area. For the first time, the combined studies and expertise of geoscientists from industry, governments, and universities have been brought together in a single volume. All those interested in the geology of the Sudbury area will welcome the many distinguished chapters in this volume.

In this, Ontario's bicentennial year, I believe it is very fitting that scientists with a wide variety of perspectives and backgrounds should collaborate to produce a work as comprehensive and descriptive as this one. The geological expertise developed through mining in the Sudbury area over the past century has led to the publication of this volume. I am confident that the wealth of material in the book will help ensure that interest in the area continues to be strong for many years to come.

PREFACE

E.G. Pye

Formerly, Director of the Ontario Geological Survey

The Sudbury Structure is one of the most scientifically and economically interesting geological structures on our planet. Since the first discovery of nickel-copper ores near the present site of the City of Sudbury in 1883, many scientific observations have been made. These are reported on in a voluminous literature.

The Sudbury Structure has attracted the interest of several generations of geologists. Without exaggeration there is probably no living geologist who is unaware of the existence of this geologically intriguing structure.

In spite of all this interest, no comprehensive descriptive work on the Sudbury Structure existed. Several of the previous, venerable publications, commonly written by one or a few authors, dealt with specific problems of Sudbury geology. The most recent one, published by the Geological Association of Canada in 1972, is entitled "New Developments in Sudbury Geology". This 1972 publication was the outcome of a special meeting on Sudbury geology by the Geological Association of Canada that discussed the evidence for and against the view that the Sudbury Structure is an impact structure, an interpretation first suggested by R.S. Dietz in the early 1960s.

The lack of a comprehensive treatise on Sudbury geology has been evident to many geoscientists who have worked or are working in the Sudbury area. Several events together initiated work on the present volume. In early 1981, D.H. Rousell, after discussing the matter with W.V. Peredery, suggested to me that the publication of a book on Sudbury geology would be worthwhile. At approximately the same time the Ontario Government, spearheaded by the Ministry of Culture and Recreation, invited all government agencies to consider contributions to celebrate the bicentenary of the Province of Ontario. These two events and the then upcoming centenary of the first discovery of nickel-copper ore in the Sudbury area in 1883, and also the fact that two of the Survey's geologists were each just completing a multi-year investigation in the Sudbury area, made it appropriate to advance further with D.H. Rousell's proposal.

Geoscientists presently working in the Sudbury area were invited to contribute to a volume on Sudbury geology to commemorate the bicentenary of Ontario and the centenary of Sudbury. The response was very encouraging. Dr. L. Kilburn (Vice-President Exploration, Falconbridge Limited) and Dr. T. Podolsky (Vice-President Exploration, Inco Limited) kindly accorded the enthusiastic cooperation of the geological staff of their companies. Researchers from four universities, the Royal Ontario Museum and three consulting companies, the staff of the Geological Survey of Canada, and the geological staff of the Ontario Ministry of Natural Resources also contributed much time and effort. This volume is the result of this unique cooperation.

The purpose of this multidisciplinary approach was to document the geological and geophysical features of the Sudbury Structure. Three authors were given the task of interpreting the features described by the other authors, two as proponents of a impact origin (W.V. Peredery and G.G. Morrison), and one as a proponent of an endogenic origin (T.L. Muir). During several field trips and geological discussions all authors had ample opportunities to present their own views and to try to influence the content of two interpretative papers. In a summary paper, A.J. Naldrett presents a personal view on the Sudbury Structure and evaluates the documented evidence presented in all the papers.

This volume will, hopefully, not only shed light on the geology of the structure and its origin but it may also stimulate further interest in Sudbury geology and initiate new research programs. It is an ongoing responsibility of the Canadian geoscience community to encourage and develop research activities on the Sudbury Structure.

It was a pleasure to work with the group of people who have prepared this volume for publication. I gratefully acknowledge the cooperation of all authors and staff of the Scientific Review Office (namely Guy Kendrick, Christine Tchoryk, R. Simon, Lyell McKinnon, and Jeanette Barron), Ontario Geological Survey. All papers of this volume were critically reviewed by geoscientists from three continents. It is a pleasant duty to thank all reviewers listed below for their constructive and thorough work:

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The geological compilation map (Map 2491, in back pocket) is based on the work of many geologists. An attempt has been made by the compiler, Burkhard O. Dressler, to acknowledge the most important contributions to this map in the marginal notes of the map. Space limitations did not allow credit to be given to all contributors who helped make this an up-to-date map. I, therefore, wish to gratefully acknowledge the input to this map by the following people.

Falconbridge Limited (Geology of Falconbridge Township and of North Range footwall):

C.J.A. Coats; D.L. Owen; M. Penstone; P. Snajdr; F.H. Toews.

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I also thank A.G. Darnley, P. Hood, S.D. Dods, and D.J. Teskey (Energy, Mines and Resources, Ottawa) who contributed an aeromagnetic map of the Sudbury area. Last but not least I wish to acknowledge the careful work by the staff of the Surveys and Mapping Branch, Ministry of Natural Resources under the supervision of P.A. Wisbey (Cartography Section), and R. Balgalvis (Drafting Services).

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MAPS

(back pocket)

Map 2491 (coloured)—Sudbury, District of Sudbury.
Scale 1:50 000.

Map NL-16/17-AM (coloured)—Sudbury, District of Sudbury.
Scale 1:1 000 000.

Aeromagnetic Map produced especially for this volume by the Geological Survey of Canada.

CHARTS

(back pocket)

Chart A—Bouguer Gravity Map of the Sudbury area and parts of Abitibi Province.
Scale 1:1 000 000.

Chart B—3 Geological Plans, Onaping-Levack area (for Chapter 14).

Chart C—Bouguer Gravity and generalized geological map of the Sudbury area.
Scale 1:100 000.

Conversion Factors for Measurements in Ontario Geological Survey Publications

If the reader wishes to convert imperial units to SI (metric) units or SI units to imperial units the following multipliers should be used:

CONVERSION FROM SI TO IMPERIAL

CONVERSION FROM IMPERIAL TO SI

SI Unit	Multiplied by	Gives	Imperial Unit	Multiplied by	Gives
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LENGTH

1 mm	0.039 37	inches	1 inch	25.4	mm
1 cm	0.393 70	inches	1 inch	2.54	cm
1 m	3.280 84	feet	1 foot	0.304 8	m
1 m	0.049 709 7	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	1.609 344	km

AREA

1 cm ²	0.155 0	square inches	1 square inch	6.451 6	cm ²
1 m ²	10.763 9	square feet	1 square foot	0.092 903 04	m ²
1 km ²	0.386 10	square miles	1 square mile	2.589 988	km ²
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha

VOLUME

1 cm ³	0.061 02	cubic inches	1 cubic inch	16.387 064	cm ³
1 m ³	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m ³
1 m ³	1.308 0	cubic yards	1 cubic yard	0.764 555	m ³

CAPACITY

1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	4.546 090	L

MASS

1 g	0.035 273 96	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 75	ounces (troy)	1 ounce (troy)	31.103 476 8	g
1 kg	2.204 62	pounds (avdp)	1 pound (avdp)	0.453 592 37	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	907.184 74	kg
1 t	1.102 311	tons (short)	1 ton (short)	0.907 184 74	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	1016.046 908 8	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	1.016 046 908 8	t

CONCENTRATION

1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

1 ounce (troy)/ton (short)	20.0	pennyweights/ton (short)
1 pennyweight/ton (short)	0.05	ounce (troy)/ton (short)

NOTE—Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries published by The Mining Association of Canada in cooperation with the Coal Association of Canada.

HISTORY AND REGIONAL STUDIES



CHAPTER 1

History of Exploration and Development, of Geological Studies and Development of Geological Concepts

P.E. Giblin

Ontario Ministry of Natural Resources, Sudbury

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INTRODUCTION

In this chapter, the history of the discovery of nickel at Sudbury and the development of the nickel mining industry into one of world stature is first outlined briefly. The history of geological work in the area is then outlined in somewhat more detail, together with the major problems and controversies that have developed as studies of this complex area have progressed.

HISTORY OF EXPLORATION AND DEVELOPMENT

In the mid-1800s, northern Ontario was largely a wilderness. The few settlements were small villages and trading posts situated on the waterways of the region. Neither roads nor railways existed, and travel was by boat in summer on the numerous lakes and rivers, and by snowshoe and sleigh in winter. It was in this setting that the first discoveries of nickel were made. Given the remoteness of the area, the difficulties of access, and above all the lack of industrial demand for the metal, it is not surprising that these first discoveries failed to attract commercial interest.

The first nickel discovery in Ontario was made about 1848 at a site on the North Shore of Lake Huron, some 70 km southwest of Sudbury. This occurrence, known as the Wallace Mine, is unrelated geologically to the great nickel deposits soon to be found at Sudbury and proved to be of no economic value.

The earliest discovery of nickel in what came to be known as the Sudbury area was made in 1856. At that time, government survey parties were engaged in running base, meridian, and range lines in preparation for a general survey and subdivision of northeastern Ontario. In the course of running a survey line, Salter

(1856) discovered considerable local magnetic attraction and noted the presence of iron in the rocks. He recognized the unusual nature of the occurrence, and reported the matter to Alexander Murray of the Geological Survey of Canada who was working in the region. Murray visited and sampled the locality. Analysis of the material showed it to contain copper and nickel. Murray published a report describing the occurrence (Murray 1857) but, presumably for the reasons mentioned earlier, the report failed to attract any interest. Several decades later, the site of Salter's and Murray's discovery was found to lie only about 200 m west of the open pit of the Creighton Mine.

Construction of the Canadian Pacific Railway through the Sudbury area westward to join British Columbia to the eastern provinces, led directly to the discovery and development of the major nickel-copper deposits of the area.

In 1883, the right-of-way for the railway had been cleared through the forest for some distance west of Sudbury. T. Flanagan, a blacksmith on the construction crew noticed an area on the right-of-way covered by gossan, and dug some holes which revealed the presence of copper sulphide. Later in the year, construction of the railbed reached the site of the gossan. A cutting in the rock was required, which exposed high-grade mineralization.

The occurrence was acquired by T. Murray, and subsequently developed as the Murray Mine. The discovery outcrop remained intact until the mid-1970s when the railway right-of-way was moved and this part of the orebody mined.

News of the discovery quickly attracted prospectors to the area. Exposed parts of the orebodies were capped by gossans which are easily recognizable accumulations of rust-coloured weathering products of sulphides. Prospectors soon realized that the gossan zones were spatially related to a variety of igneous rock

CHAPTER I

which they termed diorite. Within a few years, prospectors had discovered most of the currently known orebodies of the area.

Several companies were quickly organized to develop the deposits. Prominent among the companies to be established early in the area was the Canadian Copper Company which produced the first ore from the Sudbury area at the Copper Cliff Mine in 1886. The company also erected the first smelter in the area which began operations in 1888.

The ores were considered to be of value for their copper content. Surprisingly, the presence of nickel in the deposits was not recognized until nearly 4 years after the first discoveries of ore were made. In 1887, a shipment of ore from the Copper Cliff Mine was sent for smelting to the Orford Copper Company at Constable Hook, New Jersey. The ore proved unusually difficult to treat, and assays of the furnace products revealed the presence of nickel.

As soon as the companies realized that they owned large reserves of nickel as well as of copper, the problem of finding markets for the metal had to be faced. Total annual world consumption of nickel was only about 1000 tons in 1888, and the Sudbury mines had the potential to produce far more than this modest amount. In addition, world nickel production at the time was dominated by New Caledonia whose production was tied to the established markets in Europe.

S.J. Ritchie, first president of the Canadian Copper Company, was instrumental in securing the interest of the United States Navy in testing nickel steel for use as armour plate. Following successful tests in 1891, the United States Government appropriated \$1 000 000 to purchase Sudbury nickel matte to be used in the production of nickel steel for armour plate. This order, large for the time, greatly assisted development of the Sudbury area. Other markets for the metal developed, and production of nickel expanded accordingly. Early in the 1900s, Canadian production of nickel (all from Sudbury) overtook that of New Caledonia, and by 1915 Canada produced about 80% of the world's output. This dominance of the world market would continue for many decades during which the mining, smelting, and refining operations at Sudbury grew into a major industry.

In 1902, the International Nickel Company was incorporated, effectively merging most of the principal companies engaged in mining, smelting, and refining nickel. Among the companies amalgamated into the International Nickel Company, were the Canadian Copper Company and the Orford Copper Company. This gave the new company the benefit of controlling both the production and refining operations. A subsidiary, The International Nickel Company of Canada, Limited, formed in 1916, acquired the assets of the

Canadian operations, and constructed a nickel refinery at Port Colborne in southern Ontario. In 1928, The International Nickel Company of Canada, Limited, became the parent corporation. Research laboratories established by the company played an important role in developing new alloys and uses for nickel, and resulted in significant expansions of markets for the metal.

Two other companies were significant producers during the early decades of this century. The Mond Nickel Company, Limited, was formed in 1900 and acquired several mines. A smelter was erected at Victoria Mines, but in 1913, smelting operations were transferred to a new plant at Coniston. Matte was shipped to the company's refinery at Clydach, Wales. The British America Nickel Corporation, Limited, operated mines and a smelter intermittently from about 1917 to about 1924 when the company ceased operations. Its assets were subsequently purchased by The International Nickel Company of Canada, Limited.

For more than a quarter of a century, The International Nickel Company of Canada, Limited, and the Mond Nickel Company, Limited, effectively controlled the world's nickel industry. Prompted partly by their shared ownership of the large Frood orebody, and partly by other business concerns, the 2 companies merged in 1929, The International Nickel Company of Canada, Limited, absorbing the Mond Nickel Company, Limited.

A newcomer appeared on the scene in 1928 when Falconbridge Nickel Mines, Limited, was incorporated. This company acquired an undeveloped orebody from its parent company, Ventures, Limited (Le Bourdais 1957). The company developed the orebody, erected a smelter which commenced operations in 1930, and began shipments of matte to its refinery at Kristiansand, Norway. A program of property acquisition and exploration subsequently led to the discovery and development of several new orebodies.

Since then, Falconbridge Nickel Mines, Limited, and The International Nickel Company of Canada, Limited, have continued as the only producing companies in the Sudbury area. The latter company changed its name to Inco Limited in 1976, and in 1982 Falconbridge Nickel Mines, Limited, changed its corporate name to Falconbridge Limited.

Although Sudbury is famous as the world's largest single source of nickel, its ores yield several other commodities.

The original interest in Sudbury ores revolved around their copper content, which is approximately equal to their nickel content. Copper remains an important component: in aggregate dollar terms, it is the second most important co-product of the ores. For many years, Inco Limited was Canada's largest single producer of newly mined copper.

Also for many years, the Sudbury area was the world's leading producer of newly mined platinum group metals: platinum, palladium, iridium, osmium, rhodium, and ruthenium. In recent years, this pre-eminent position has been lost, but because of Sudbury's production, Canada remains the world's third largest producer of platinum group elements.

Gold, silver, cobalt, selenium, tellurium, and sulphur are also currently produced. Iron-ore pellets were formerly produced.

The peak of Ontario nickel production was reached in 1974, when 209.0 million kg were produced, having a value of \$749.7 million or a value of \$1622.4 million in terms of 1982 dollars (Weatherson 1983, p.237). In 1981, Ontario nickel production was 130.2 million kg having a value of \$1001.2 million or a value of \$1138.2 million in 1982 dollars (Weatherson 1983, p.237).

To help put these figures in perspective, in 1981, Ontario produced 18.6% of the world's nickel. The value of all mineral commodities produced in Sudbury represented 38.8% of the value of Ontario's total mineral production in 1981, and 12.4% of the value of Canada's mineral production exclusive of fuels in 1981.

Inco Limited continues to produce more nickel than any other company in the world. For 1981, the company reported total Canadian ore production of 12.1 million tons, grading an average of 1.42% nickel and 1.09% copper (Inco Limited 1981). Most of the production was derived from the Sudbury area, where most recently, in 1983, the company operated 9 mines, 2 concentrators, a smelter, nickel and copper refineries, and a coinage-strip rolling mill.

For 1981, Falconbridge Nickel Mines Limited reported Canadian ore production (all from Sudbury) of 3.0 million tons grading an average of 1.25% nickel and 1.01% copper (Falconbridge Nickel Mines Limited 1981). In 1983, the company operated 7 mines, 2 concentrators, and a smelter in the Sudbury area.

In the century that has elapsed since the first major discovery of nickel was made in the area, Sudbury has grown from a small railway construction and lumbering village, having a population of about 300 persons, to a modern metropolitan centre having a population of approximately 158 000. The growth of the area's mining, smelting, and refining industry has provided employment for many thousands, and has provided Canada with a major source of industrial raw materials and new wealth.

Because Canadian industries consume only a small percentage of the nickel that can be produced, most of the nickel is exported, and is an important source of foreign exchange earnings.

Since World War II, growing competition from foreign producers has reduced Sudbury's share of the world nickel market from 80% to about 18%. Although Sudbury's share of the market declined, for most of this period, the tonnage of nickel produced rose as the total market grew. Within recent years, foreign competition and the world-wide recession have adversely affected the industry. There is the threat of added competition from possible future production of nickel-bearing sea bed nodules.

The nickel producers of the area have streamlined their operations in the face of this competition. Commenting on the reserves of nickel ore, Anders and Mohide (1980) stated "there is no geological reason to fear that Ontario nickel production will not continue long into the next century".

HISTORY OF GEOLOGICAL STUDIES AND DEVELOPMENT OF GEOLOGICAL CONCEPTS

After nearly a century of geological work, the major features of Sudbury geology are well established. Sudbury is world famous in the geological literature because of the great economic value of the area's mineral deposits, and the many unusual, and in some cases, apparently unique features exposed here. Most text books dealing with general geology, economic geology, and petrology, discuss aspects of Sudbury geology. Their descriptions are necessarily limited in scope, somewhat generalized and simplified, and do not do justice to the great complexity of the area.

Sudbury geology seems to have intrigued most of those who have come in contact with it. This in turn has led to a great deal of research work, and the resulting literature is large: so much so that as early as 1906, Barlow referred to it as "voluminous", a sentiment that has been echoed by many writers in later years. Despite the large amount of work done, new problems and controversies continue to arise. This is testimony to the complex, often seemingly contradictory relationships to be found in the area.

Some features are well established. A brief summary may help the reader of this volume to place the development of geological knowledge and concepts in perspective, and enable him to better appreciate these developments.

The sulphide deposits, with their contained nickel, copper, platinum-group metals, and other metals, are associated with a large body of igneous rock known as the Sudbury Igneous Complex. In previous writings, the Complex was known as the Nickel-Bearing Eruptive, the Sudbury Nickel Irruptive, and as the Nickel Irruptive.

This intrusion outcrops as an elliptical ring having a major axis 60 km long striking northeast, and a minor axis 27 km long. It grades from an outer ring of norite through a transition zone of gabbro to an inner ring of granophyre, termed micropegmatite in the earlier literature. The outer contact of the body generally dips inwardly toward the centre at between 30° and 50°, but it may dip more steeply and locally dips outward.

The ore deposits are found around the outer, lower edge of the norite, and in dike-like bodies that either radiate outward from the base of the norite or occur in Footwall rocks parallel to the main Complex. The close spatial association of the ore deposits with the norite led early to the concept of a genetic relationship between the two, a concept that is generally accepted. The nature of the relationship is uncertain, and 3 principal hypotheses have been advanced. These are:

1. The ores are magmatic segregation deposits, the sulphides having been introduced in solution in the main body of magma, and during crystallization settling under the influence of gravity to the base of the norite.
2. The sulphides were introduced by hydrothermal fluids.
3. The sulphides were introduced as immiscible sulphide liquid suspended in the silicate magma of separate, perhaps younger, noritic intrusions.

Much discussion has also centred on:

1. the shape and character of the Sudbury Igneous Complex itself
2. on the nature and origin of the unusual rocks of the Sudbury Breccia and of the Onaping Formation
3. the origin of the Sudbury Structure, a collective term embracing the Sudbury Igneous Complex, nearby rocks, and associated structural features

Answers to the questions raised by workers in the area are of scientific value and, are also of great potential economic importance.

The following review of the development of geological knowledge of the area and of the concepts developed is largely chronological in nature. This approach has its drawbacks and occasionally, in order to trace the work upon a certain topic, the work on that topic alone is described before resuming the general chronological review.

Although some of the major lake and river systems of area had been traversed in 1856 by Murray of the Geological Survey of Canada, no comprehensive geological map existed at the time of the ore discoveries. To remedy this deficiency and to assist prospectors working in the area, the Survey sent R. Bell, assisted by A.E. Barlow, to Sudbury in 1888 to begin a program of regional mapping. Bell's resulting map, published in 1891 at a scale of 4 miles to 1 inch, is the first geological map of the area.

As his map illustrated, and as his report described (Bell 1891a), the nickel-copper deposits were always found intimately associated with mafic rocks he classified in the field as "greenstone", diabase, and diorite, and were associated particularly with a variety he termed diorite breccia. Mineralization was concentrated at the contact of the mafic rocks with other rocks. He recognized the existence of a central geological basin, and noted 2 principal areas underlain by the mafic rocks which are presently known as the North and South Ranges of the Sudbury Igneous Complex. The mapping coverage did not reveal the continuity of the mafic rocks around the basin. He briefly discussed the origin of the ores (Bell 1891a, 1891b), suggesting that they formed as a result of differentiation from a magma.

Petrographic studies by von Fouchon (1892) and Williams (1891) of the rocks described in the field as "greenstone", diabase, and diorite, revealed the presence of orthorhombic pyroxene, indicating that the rock was more properly classified as norite.

Walker (1897) observed the gradation of norite into granophyre, recognized that the norite and granophyre were also basin-shaped, and suggested that the Complex was continuous around the basin.

A decade after the publication of Bell's map, Barlow returned to the area to carry out further work. In 1904 he published 2 maps of the South Range, at a scale of 1 inch to 1 mile, and described the geology and ore deposits of the area. His work illustrated the major 2-fold subdivision of the Complex into a lower norite member and an upper granophyre member, the gradational nature of the contact between them, and the localization of orebodies along the lower, outer edge of the norite. He recognized the importance of embayments in the Footwall at the base of the norite and of dike-like extensions of norite in the outer wallrocks as hosts for ore. The dike-like extensions were termed "offsets", a term which persists today in the literature and in local usage. Barlow appears to have introduced the name "Nickel-Bearing Eruptive" for the norite-granophyre body, a term which subsequently became modified and familiar in the literature as the Nickel Irruptive and as the Sudbury Nickel Irruptive. Barlow (1904, 1906) also favoured origin of the ores through magmatic differentiation.

The origin of the ores has been a matter of both scientific and practical interest since their discovery. As noted earlier, both Bell and Barlow favoured origin through magmatic differentiation. Bell (1891a, p.50F) and Barlow (1908, p.129-130) however, suggested some modification had occurred through the action of hot aqueous solutions. Nevertheless, Dickson (1903) concluded that the ores did not form by magmatic differentiation, but by hydrothermal replacement.

The provincial government began geological work in the Sudbury area in 1902, when A. P. Coleman commenced mapping for the then Ontario Bureau of Mines. His map at a scale of 1 ½ inches to 1 mile, published in 1905, showed for the first time that the Complex was continuous around the basin. He considered the Complex to have the form of a laccolithic sheet, 1 ¼ miles thick, 35 miles long and 17 miles wide, that had been folded into a syncline. It was noted that the ore-bodies occurred around the margin of the norite or along dike-like offsets from the norite. He believed the ores had segregated from the magma, in part at least, under the influence of gravity. The ore deposits were classified as marginal deposits or offset deposits, a general classification still in use (Coleman 1905, p.2, 19). In 1913, Coleman published the results of his further work, together with a revised edition of his earlier map.

An additional view concerning the origin of the ores was put forward in 1914 by Howe, who suggested they had been injected as a sulphide melt. This hypothesis was supported by Bateman (1917).

In 1915, the Province of Ontario established the Royal Ontario Nickel Commission to study the nickel industry and to assess the feasibility of establishing nickel refining facilities in the province. As part of the Commission's activities, C.W. Knight studied and described the ore deposits of the Sudbury area. He noted that much of the sulphide mineralization comprised the matrix for some breccias in and adjacent to the norite; suggested that fragments in the breccias were replaced to varying degrees by sulphides; and further suggested that wallrocks of orebodies were "universally replaced or impregnated by ore whether they consist of norite, granite, greenstone, or any other rock" (Knight 1917, p.132). These points he took as evidence of hydrothermal replacement, and stated that sulphides had been introduced by heated circulating waters, possibly emanating from the same deep-seated reservoir of igneous material that had given rise to the norite-granophyre complex.

Coleman believed that the norite-granophyre body had been emplaced as a sill, intruded along the contact between the rocks now classed as the Huronian Supergroup and the Whitewater Group. Based on the evidence of steep to reverse-dips of the norite on the South Range, Knight suggested that the Complex had been intruded as a ring-dike around what he assumed to be the down-faulted block represented by the basin. Knight also discussed the age relations of the norite and of the Creighton and Murray Granite Plutons on the South Range, a point that has generated much controversy. Since the granites form wallrocks and host-rocks for some of the ore deposits, the age of the granites is an important factor in understanding the origin of the ores. Knight agreed with Coleman in believing the

Murray Pluton to be younger than the norite. He suggested that the Creighton Pluton is also younger than the norite, but pointed out the conflicting views of Barlow and Coleman.

Wandke and Hoffman (1924) supported the concept of a hydrothermal origin for the ores.

Phemister (1926) investigated the Complex and the ore deposits for the then Ontario Department of Mines. He concluded that the norite and granophyre were separate intrusions, the norite being the older; and that the Creighton and Murray Granites were younger than the Complex. It is well established that the Copper Cliff Offset intrudes the Creighton Pluton, consequently Phemister was led to conclude that the offsets are younger than the norite. He believed the ores to have been deposited by ascending hydrothermal solutions. In 1937, Phemister reviewed some of the problems associated with the Igneous Complex.

The geology of the Sudbury Basin area was mapped in 1927 and 1928 by Burrows and Rickaby for the Ontario Department of Mines. Their report (Burrows and Rickaby 1930) also described the lead-zinc-copper-silver deposits that occur within the Basin.

Coleman, Moore, and Walker (1929) restudied the Complex, and restated their conclusions that the norite and granophyre were formed from one body of magma which had undergone differentiation in place while still completely fluid, and that the ores had formed by magmatic differentiation. In a subsequent contribution, Walker (1935) interpreted differentiation of the Complex in terms of the sinking of heavy crystals from the magma during cooling.

W.H. Collins of the Geological Survey of Canada carried out field work in the period 1928 to 1935, describing the results of his studies in a series of papers (Collins 1934, 1935, 1936, 1937). His maps, at a scale of 1 mile to 1 inch, were published posthumously, with some additional data provided by H.C. Cooke (Collins and Cooke 1938a, 1938b, 1947a, 1947b).

Collins' study of the Complex suggested that the norite-granophyre contact was transitional, concurring with a conclusion reached earlier by Barlow (1904) and Coleman (1913). On his maps he defined a transition zone, thereby introducing a 3-fold subdivision of the major units of the Complex. He believed the Complex had been intruded as a sill which differentiated in place, and from which the sulphide ores had settled to concentrate at the base; and that subsequent movements resulted in molten sulphides and offset magma being injected into fracture zones in the wallrocks (Collins 1937, p.39-41). Collins also pointed out that the rock of the offsets, while chemically similar to the norite, is mineralogically quartz diorite (Collins 1937, p.24).

CHAPTER I

In the process of preparing Collins' maps for publication, Cooke carried out field work in the area, and published his observations and conclusions on certain aspects of Sudbury geology in 1946.

Yates (1938) reviewed the results of studies of the Complex by staff of The International Nickel Company of Canada, Limited. In a second paper (Yates 1948), discussed the geology of the company's operating mines and introduced an important concept concerning the localization of the ores.

Yates classified the ore deposits into 3 major types: disseminated ore confined almost entirely to quartz diorite; massive sulphide ore occurring in almost any rock type, but usually along definite fault or breccia zones; and stringer ore consisting of massive sulphide stringers occurring in a wide variety of brecciated country rocks. He suggested the ores were partly of hydrothermal replacement origin, and partly of deep-seated contact metamorphic origin.

The quartz diorite was recognized as being distinct from the norite, with which it was considered to be genetically related. Although the relationships were not always clear, he believed the quartz diorite to be intrusive, mainly along the outer contact of the Complex, and into the norite as well.

Yates pointed out that most of the ore occurs in quartz diorite or very close to it, and that there is very little ore of the massive or disseminated sulphide type in the true norite of the Main Mass of the Sudbury Igneous Complex. In the case of the Foy Offset, he noted that the quartz diorite was in sharp contact with norite, that relative ages were impossible to determine from the evidence at this locality, but that "it is clear that they are different rocks and it is significant that the mineralization is confined to the quartz diorite and stops abruptly at the norite contact" (Yates 1948, p.605).

Yates' discussion was based on evidence largely derived from deposits on the South Range and in the offsets, which differ in some respects from the North Range deposits of the Levack area. He noted that the ore deposit of the Levack Mine was an exception to the above generalization regarding quartz diorite: that at the Levack Mine, a type of granite breccia takes the place of quartz diorite as the principal host-rock for the ore.

The Falconbridge deposit, a large deposit whose structural control by a major fault zone is pronounced, was described in papers by Davidson (1948) and Lochhead (1955). Davidson concluded that mineralization was introduced by hydrothermal solutions, probably derived from the same magma source as the norite. Lochhead (1955, p.48) suggested that the sulphides were deposited from ascending solutions, which also altered part of the main mass of the norite to produce quartz diorite.

General geological features of other mines have been described as follows: the Hardy Mine by Mitchell and Mutch (1956, 1957), the Frood-Stobie Mine by Zurbrigg *et al.* (1957), the McKim Mine by Clarke and Potapoff (1959), the Strathcona Mine by Cowan (1968), and several mines were briefly described by Souch, Podolsky *et al.* (1969). Abel *et al.* (1979) described copper mineralization in the Footwall complex of the Strathcona Mine, and in 1981, Abel described details of the structure of the copper zone.

Although Sudbury is best known for its nickel-copper ores, which occur outside the central basin, several deposits of lead-zinc-copper-silver-gold are found within the Basin. The geological setting, composition, and origin of these deposits are distinct from those of the famous nickel-copper deposits, and were described by Martin in 1957.

The Sudbury area is noted for the common presence of a distinctive breccia, which occurs in a zone many km wide surrounding the Sudbury Igneous Complex. The breccia irregularly pervades all rocks surrounding, and older than the rocks of the Complex. It is generally considered to be younger than the rocks surrounding the Complex, but older than the Complex itself. In the early years of geological work in the area, the breccia was known as crush conglomerate, more recently, it has come to be known as Sudbury Breccia. Geologists working in the area are generally agreed that formation of the breccia is related to the sequence of events responsible for formation of the Sudbury Structure, intrusion of the Sudbury Igneous Complex, and ultimately, formation of the ores.

Major studies of the breccia have been carried out by Fairbairn and Robson (1944, 1942), Speers (1957), and by Dupuis *et al.* (1982). These authors favour an origin through the action of explosive high-pressure fluids related to volcanism or diatremes. Wilson (1956) noted that the observed sequence of events places formation of the Sudbury Breccia very close to the time of intrusion of the Sudbury Igneous Complex, and attributed formation of the breccia to the magma forcing the country rocks aside. As will be noted more fully later, several recent authors have attributed origin of the Sudbury Breccia to sudden severe compression generated by meteorite impact.

In 1953, after an interval of a quarter of a century, the Ontario Department of Mines again began work in the Sudbury area, work which has continued intermittently to the present. Thomson mapped several townships and key localities, prepared a regional compilation map at a scale of 1 inch to 1 mile, and put forward papers discussing Sudbury geology and the sulphide deposits (Thomson 1957, 1959, 1969). Williams (1957) very briefly investigated the Onaping Formation of the Sudbury Basin, and Phemister (1957) studied the Copper Cliff rhyolite. Langford (1960)

continued the program of mapping at a scale of 1 inch to ¼ mile that had been started by Thomson (1957). Card commenced mapping, chiefly in the Huronian area southwest of Sudbury, published a compilation map of the Sudbury mining area at a scale of 1 mile to 1 inch, and summarized the results of much of his work in 1978.

The Onaping Formation consists of a thick sequence of predominantly pyroclastic rocks and occurs only within the Sudbury Basin where it overlies, and is intruded by, granophyre of the Sudbury Igneous Complex. Like so many features of Sudbury geology, the Onaping Formation is complex in detail, and its origin is controversial. The formation has become the subject of considerable recent interest as workers in the area have recognized that the origin of this unit has an important bearing on the origin of the Sudbury Structure.

Burrows and Rickaby (1930) concluded that the Onaping Formation was of volcanic origin. Thomson (1957) described the formation, and was instrumental in having the Ontario Department of Mines engage Howell Williams, a noted volcanologist, as a consultant. Williams (1957) concluded that the Onaping Formation represents a vast accumulation of rapidly deposited glowing avalanches in a basin located approximately on the site of the present Sudbury Basin. He believed that the glowing avalanches were discharged from fissures located near the present inner margin of the granophyre, and that the fissures coincided with channelways through which rhyolite dikes had earlier been intruded to supply Pelean domes. He correlated the Onaping Formation with sections of the Stobie Formation outside the Sudbury Igneous Complex (a correlation not generally accepted by other workers). Also, Thomson and Williams (1959) suggested that a highly siliceous breccia unit at the base of the Onaping Formation is brecciated rhyolite.

It was also suggested (Williams 1957; Thomson 1969) that the rapid discharge of the more than 300 cubic miles of avalanche debris caused sufficient drainage of the magma reservoirs to cause further sinking of the basin, forming a deep volcano-tectonic sink. Intrusion of the norite and granophyre, as successive injections, was postulated to have then occurred along ring faults surrounding the basin. The Sudbury Igneous Complex was thus considered to have the form of a ring-dike.

Wilson (1956) suggested that the Sudbury Igneous Complex was instead funnel-shaped, and that at depth it might be associated with ultramafic rocks. He also discussed the origin of the Sudbury Breccia, the ages of the Creighton and Murray Plutons, and concluded that the Creighton Pluton is pre-norite and that the age of the Murray Pluton is uncertain.

Hamilton (1960) suggested that the Sudbury Igneous Complex is extrusive in origin, a viewpoint that has not found support.

Stevenson, who had carried out extensive work on the Sudbury Igneous Complex and the Onaping Formation, made several contributions (Stevenson 1961, 1963, 1972; Stevenson and Colgrove 1968). In 1961, he showed that the thin siliceous basal breccia at the base of the Onaping Formation was a mappable unit over much of the East and South Ranges, consisting largely of brecciated quartzite. He considered that the tuffs and tuff-breccias of the Onaping Formation comprise an ash-flow sheet (Stevenson 1972).

Thode *et al.* (1962) investigated sulphur isotope ratios in rocks and ores of the area. They concluded that the results obtained for the Sudbury Igneous Complex and related ores are consistent with gravity controlled differentiation from a single sheet-like body of magma.

Hawley (1962) summarized the results of many years of study of the Sudbury ores, and presented a comprehensive discussion of the mineralogy, metals, and distribution of the important ore minerals and metals within the deposits. He also discussed the Sudbury Igneous Complex briefly noting that it exhibited crystal layering of a type formed by crystal settling; that the Complex appeared to have been intruded as one mass essentially saturated with sulphides from which the ores separated during cooling as immiscible sulphide liquids. Post-magmatic effects, of minor importance, were thought due to remobilization by younger intrusions and some hydrothermal and supergene alteration.

He briefly discussed the quartz diorite, noting that it seemed always confined to the basal parts of the Sudbury Igneous Complex and to the underlying Offset Dikes, and noting that it almost everywhere contains abundant rounded fragments of footwall rocks. Further, he stated that it formed early in the history of the Sudbury Igneous Complex, during the time at which magmatic sulphide liquids were separating and settling from the silicate phase. He further suggested that the quartz diorite may have formed from a more basic parent by either assimilation of acidic wallrock fragments, or through acquisition of silica and volatiles acquired with the sulphide ores.

Experimental work on the iron-nickel-sulphur system and on silicate-sulphide relations was carried out by Kullerud and Yoder (1963), and applied to Sudbury ores by Kullerud (1963). Kullerud (1963) suggested that sulphur present in the ores was derived from an external source, moved into the intrusion, and reacted with it to form nickel and copper sulphides. This view was subsequently modified by him (Naldrett and Kullerud 1967b).

Hawley (1965) described mineral zoning in the Frood Deposit, discussed the application of the work of Kullerud and Yoder (1963), suggested that the ore-forming fluids consisted of immiscible silicate (quartz diorite) and sulphide liquids. Hawley further suggested that there was a time gap between crystallization of the norite and injection of quartz diorite and ore, though it need not have been great.

In a landmark paper, Dietz (1964) suggested the Sudbury Structure was an astrobleme, whose formation was initiated by the impact of a large, copper-rich, nickel-iron meteorite in Middle Precambrian time. He suggested that a meteorite struck the Earth at Sudbury, exploded, and excavated a shallow crater about 30 miles across and 2 miles deep; that shock waves spread outward causing severe brecciation in the country rocks, giving rise to the Sudbury Breccia and forming shatter cones in the wallrocks of the crater. He further suggested that the ores were splash-emplaced material from the meteorite (a view he amplified in 1972), and that the quartz diorite represented impact-liquified country rock. It was proposed that fracturing of the crust and heat resulting from impact resulted in generation of magma in the deep crust, which welled up into the crater, cooled, and differentiated to form the norite-granophyre complex. The Onaping Formation was thought to have formed through explosive degassing of the crustal zone of the cooling magma. It was suggested that before the crater was completely filled, sediment was poured into it to form the upper formations (the Onwatin and Chelmsford Formations) of the Whitewater Group. Dietz (1964) emphasized that his hypothesis of a cosmic parenthood of the ores might well be wrong, and that it should not itself negate other aspects of the impact thesis which stood on independent evidence.

Interest in the special problems of Sudbury geology has generally been at a fairly high level, but Dietz' paper resulted in a greatly renewed interest, much controversy which continues to this day, and much useful work. Certain aspects of his basic thesis, those of meteorite impact being responsible for formation of the Sudbury Breccia and shatter cones, and indirectly responsible for the magmatism giving rise to the Sudbury Igneous Complex, are accepted by many, but not all workers in the area. His concepts concerning origin of the ores and of the Onaping Formation, and of the later history of the Basin have few, if any, adherents.

Another major contribution is that of Souch, Podolsky, and geological staff of The International Nickel Company, Limited, first presented at a meeting in 1966, and published in 1969. They stated that the ores were part of, and confined to, a discontinuous marginal facies of the main Sudbury Igneous Complex. The marginal facies, termed the Sublayer, is a sulphide- and inclusion-bearing noritic rock, which occurs at intervals below the norite. They recognized 3

Sublayer environments: the North Range, South Range, and Offsets.

The North Range Sublayer is a noritic rock containing sulphides and rounded exotic fragments of peridotite, pyroxenite, and gabbro, and angular fragments of Footwall rocks. It may grade into a leucocratic phase, termed granite breccia, characterized by the presence of rounded exotic inclusions of peridotite, pyroxenite, and gabbro, as well as by Footwall rock fragments, and by the variable presence of sulphides. On both ranges, the contact between the Sublayer and norite was stated to be generally abrupt. In the offset environment, dikes of sulphide- and inclusion-bearing quartz diorite project into the Footwall from the base of the norite.

Souch, Podolsky *et al.* (1969) presented a new classification of ore types, noted the orebodies exhibit characteristics that reflect the differing spatial environments in which they occur, and described representative deposits. These authors concluded that the ores are products of crystallization of an inclusion- and sulphur-rich silicate magma.

The results of radiometric dating suggested that the norite and Sublayer may be contemporaneous, and that both were older than the granophyre.

Even though these authors did not discuss the point, the Sublayer as defined by Souch, Podolsky *et al.* (1969) appears to be, in part, the same unit described as quartz diorite by Yates (1948) and Hawley (1962, 1965).

Recognition and definition of the Sublayer as a distinct unit of the Sudbury Igneous Complex has aided both exploration work and scientific studies. Recognition of exotic ultramafic inclusions in the Sublayer has provided new evidence bearing on the origin of the Complex and of the ores.

The Sublayer was further described by Pattison (1979), who recognized 2 major variants: igneous-textured gabbro-norites and metamorphic-textured leucocratic breccias, both characterized by the presence of sulphide and abundant xenoliths. The 2 types were termed, respectively, igneous Sublayer and leucocratic breccia. Pattison concluded that the quartz diorite of the offset environment was altered igneous Sublayer, and was not a separate type of Sublayer. He noted the fragmental nature of disseminated sulphides in leucocratic breccia, in contrast with the interstitial nature of disseminated sulphides in the adjacent igneous Sublayer, and suggested that the sulphide fragments may have been inherited from a pre-existing source. Evidence bearing on the age of the Sublayer relative to that of the Main Mass of the Sudbury Igneous Complex was discussed, and he concluded that the Sublayer is older than the norite. Interrelationships of the igneous Sublayer and leucocratic breccia were

described, and it was suggested that the 2 types were emplaced simultaneously, followed by readjustments giving rise to mutually intrusive relationships.

Two hypotheses, both invoking meteorite impact as the initiating mechanism, were advanced by Pattison (1972) to account for origin of the Sublayer. The first involved segregation of a sulphide-rich magmatic differentiate, formed in the lower levels of an impact-triggered magma, the segregated fraction then being injected along the unconformity between Footwall rocks and the overlying Onaping Formation. A second intrusive phase followed and crystallized to form the norite-granophyre mass. According to this hypothesis, meteorite impact served only as a triggering mechanism for relatively conventional magmatic processes. The second and preferred hypothesis envisioned the igneous Sublayer as a mixture of sulphide-rich impact melt and brecciated mafic to ultramafic Footwall rocks derived from the deeper levels of the crater structure, which was emplaced along the walls of the crater. It was suggested that the sulphides were derived from previous concentrations in mafic to ultramafic magmatic country rocks. As in the previous case, intrusion of the Main Mass of the Sudbury Igneous Complex then followed. Pattison (1979) suggested that in either case, the leucocratic breccias formed by mechanical attrition of brecciated Footwall rocks as the igneous Sublayer was intruded.

Dietz's (1964) paper was soon followed by several papers concerned with various aspects of the astrophysical hypothesis. Guy-Bray and (Inco) Geological Staff (1966) described shatter cones in the Footwall rocks of the Sudbury Igneous Complex. French (1966, 1968a) described shock metamorphism as a geological process. French (1968b) described petrographic evidence typical of shock metamorphism from the Onaping Formation. French (1968b, p.383) considered that "these observations establish a strong similarity between Sudbury and other structures for which an impact origin is either proven or strongly indicated". He concluded that the Sudbury Basin was formed by meteorite impact, and suggested that the Onaping Formation represents a "fallback breccia", composed of material explosively excavated from the crater by the impact, and immediately redeposited (French 1968b, p.408). In later papers (French 1969, 1970), he suggested that large meteorite impacts may control emplacement of internally-generated magmas through "unroofing" of the magma chamber, or by the production of deeply extending zones of weakness below the crater. It was further suggested that the Sudbury Igneous Complex was formed from magma produced at depth, that ascended along fractures below the crater and spread out along the contact between the Footwall rocks and the Onaping Formation.

During the period 1963 to 1975, several studies of the petrology of the Sudbury Igneous Complex were published.

Stevenson (1963) described the upper contact phase of the granophyre, and suggested that the definition of the granophyre be extended to include a fine-grained upper phase which, because of its colour in outcrop, he termed "pepper-and-salt micropegmatite" (granophyre). He noted that this phase graded into normal granophyre on its lower contact, and on its upper surface extended irregularly into the basal quartzite breccia and the tuffs of the overlying Onaping Formation. Quartz pseudomorphic after tridymite was found around and inside inclusions of quartzite and granite in the lower part of the "pepper-and-salt micropegmatite" (granophyre) and upper part of the normal granophyre. This, together with spherulitic intergrowths, was interpreted by Stevenson (1963) to indicate a high intrusion temperature in the 800° to 900°C range, and rapid cooling of the granophyre.

Naldrett and Kullerud (1965, 1967a, 1967b) carried out detailed studies of the Strathcona Mine on the North Range, and subdivided the norite member of the Sudbury Igneous Complex into 4 units in the vicinity of the mine. Naldrett and Kullerud (1967b) classified the basal unit of the Main Mass of the Complex as felsic norite, and distinguished 3 younger noritic units which they named mafic norite, xenolithic norite, and hanging wall breccia.

Naldrett and Kullerud (1967b) suggested that the Sudbury Igneous Complex was emplaced as a funnel-shaped body of magma, which then cooled and differentiated giving rise to a fractionated sequence ranging in composition from dunite to felsic norite. This was believed to have been followed by intrusion of mafic norite magma carrying some sulphide liquid in suspension, brecciation of mafic and ultramafic material at depth within the Complex, and then by intrusion of xenolithic norite magma which carried droplets of liquid sulphide in suspension. Naldrett and Kullerud (1967b) suggested that the xenoliths and the sulphides settled toward the base of the intrusion with some sulphides penetrating the Footwall rocks beyond the intrusion and some remaining trapped in the intrusion. Sulphide crystallization was interpreted to have been followed by brecciation and crushing along the contact between the Sudbury Igneous Complex and the Footwall gneiss, giving rise to the Footwall Breccia and main-zone ore.

In 1968, Naldrett and Kullerud slightly amplified their views, stating that the sulphides were carried up from depth as droplets of immiscible sulphide-oxide liquid suspended in the silicate magma of the xenolithic norite.

Stevenson and Colgrove (1968) described the results of several years' detailed mapping and petrographic work. Classifying the Sudbury Igneous Complex as a layered intrusion, these authors (Stevenson and Colgrove 1968, p.28-29) pointed out that "the layering in the Sudbury Irruptive is quite gross and can only be brought out by detailed mapping and microscopy with careful attention to the petrography".

Stevenson and Colgrove (1968) described 4 subdivisions of the norite member, including within their uppermost norite subdivision the rock that is transitional into the granophyre. Three subdivisions of the granophyre were described. The major differences between the North and South Ranges were described, and these authors noted the presence of abundant xenoliths and of numerous small granite intrusions in certain stratigraphic zones of the South Range. These authors concluded that the Sudbury Igneous Complex formed through fractional crystallization *in situ*.

Naldrett *et al.* (1970) published the results of a detailed study of the petrology of the Sudbury Igneous Complex, describing textural and modal variations, as well as compositional variations in plagioclase, augite, and hypersthene along several cross-sections of the Complex. From the North Range, these authors described the felsic norite, the overlying oxide-rich gabbro (formerly called transition zone), and granophyre while from the South Range, the quartz-rich norite, South Range norite, upper gabbro (formerly transition zone), and granophyre were described.

These authors concluded that the South Range norite is a mesocumulate, the felsic norite and the gabbros being orthocumulates. Phase layering was described as being present in the Sudbury Igneous Complex, with cumulus minerals appearing and disappearing at different levels within the intrusion, defining distinct continuous horizons.

Naldrett *et al.* (1970) found cryptic variation in the composition of plagioclase in felsic norite and oxide-rich gabbro of the North Range, and in South Range norite and upper gabbro of the South Range. As well, cryptic variation was shown by augite and hypersthene in norite and gabbro of the North Range. The variation is consistently one of enrichment of the minerals in their lower melting point end-members upward in the sequence. On the basis of the irregularities in the iron enrichment trend of pyroxene near the top of the granophyre, these authors suggested parts of this unit might have been emplaced after the Main Mass of the intrusion. Naldrett *et al.* (1970, p.146-147) concluded that "a continuous fractionation by gravitational crystal settling has operated over the interval covering the norites, gabbros and at least the lower part of the micropegmatite" (granophyre).

The extreme outer part of the quartz-rich norite of the South Range was considered to closely approximate the composition of the liquid part of the original intrusion. The quartz-rich nature of the rocks of the Complex was suggested to be the result of mixing with considerable felsic material and assimilation at an early stage in the history of the intrusion, perhaps at depth before emplacement into its present position.

Following several previous authors (for example, Wilson 1956; Souch, Podolsky *et al.* 1969; Stevenson and Colgrove 1968), Naldrett *et al.* (1970) suggested that the intrusion was funnel-shaped at depth, and that rocks of the South Range have been up-faulted about 3 miles with respect to the North Range along steep, southerly dipping faults, thus exposing a deeper section through the intrusion than that exposed on the North Range.

Greenman (1970) investigated the Footwall Breccias in the vicinity of the Strathcona Mine on the North Range, concluding that brecciation of Footwall material occurred both immediately before, and shortly after, emplacement of the Complex.

Following a study of the marginal mafic rocks on the North Range of the Sudbury Igneous Complex, Hewins (1971) concluded that the mafic norite member defined by Naldrett and Kullerud (1967b) is a member of the main body of the Complex.

Naldrett *et al.* (1972) described Sublayer rocks from the North Range and their relationships to the overlying main Sudbury Igneous Complex. These authors stated that the bulk of the ore is thought to have been introduced with mafic Sublayer intrusions rich in ultramafic inclusions and particularly rich in sulphides. It was noted that contacts of the intrusions with the Complex are sharp and that evidence bearing on their respective ages is contradictory, although it was tentatively suggested that the Sublayer may be younger (Naldrett *et al.* 1972, p.211). These authors proposed a sequence of observed features, noting that the model was speculative and one of many that might be proposed (Naldrett *et al.* 1972, p.212-213).

The petrology of the granophyre was described by Peredery and Naldrett (1975), who recognized 2 distinct rock types: 1 that is granophyre-rich, termed the "granophyric micropegmatite", typical of the main mass of the granophyre, and 1 that is rich in plagioclase, termed the "plagioclase-rich rock". It was concluded that the plagioclase-rich rock is a phase of the upper part of the oxide-rich gabbro which was split off from the remainder of this unit by a later injection of the granophyre-rich phase. These authors considered that the granophyre-rich phase represents an extreme differentiate of the intrusion, which accumulated over the top of the intrusion in the presently unexposed zone in the centre of the Sudbury Basin, then was injected laterally toward the edges of the structure on top of the

norite and gabbro members. These authors also suggested that much of the rock that Stevenson (1963) had described as an upper chilled phase of granophyre, the "pepper-and-salt micropegmatite", is either a highly recrystallized matrix of the basal breccia of the Onaping Formation or a melt rock believed to be related to meteorite impact (Peredery and Naldrett 1975, p. 165-166). The melt rock was described in other papers by Peredery (1972a, 1972b).

The continuing interest in Sudbury geology, rekindled in part by Dietz' astrobleme hypothesis, led to the holding of a special session at the 1971 Annual Meeting of the Geological Association of Canada. Many of the papers presented at the meeting were subsequently published (Guy-Bray 1972a) and added new insights into several aspects of Sudbury geology. Understandably, many of the papers dealt with aspects of the meteorite impact hypothesis: Guy-Bray (1972b) reviewed evidence for and against impact; in separate papers Dence (1972), French (1972), and Dietz (1972) advanced views in favour of impact, citing petrographic evidence of shock metamorphism and to a lesser extent, the presence of shatter cones, in support of their arguments.

Two papers, one by Stevenson (1972) and another by Peredery (1972a), dealt with the key problem of the origin of the enigmatic Onaping Formation.

Stevenson (1972) noted that the formation is pyroclastic, but that its origin has always been a problem. Petrographic features were interpreted by Stevenson as indicative of ash-flow origin; the composition was stated to range from rhyodacite to dacite; and the formation was interpreted as an ash-flow sheet erupted from a fissure or fissures.

Peredery (1972a), on the other hand, concluded that the Onaping Formation formed as a consequence of meteorite impact. He subdivided the formation into 4 units: a basal breccia, the overlying grey Onaping, the uppermost black Onaping, and melt rocks. The melt rocks occur as irregular masses on top of the basal breccia, project into the overlying grey and black members, and appear to be intrusions in some cases, flows in others.

Peredery (1972a) interpreted the basal breccia as the earliest fall-back material or possibly brecciated country rock in place, analogous to the Bunte Breccia of the Ries crater in Germany; the grey Onaping as the true fall-back breccia analogous to the Ries crater suevite. The finer grained, carbonaceous black Onaping was interpreted as a wash-in deposit derived from the fall-back and brought back into the crater by a tsunami-like wave. The melt rocks were stated to be products of fusion of pre-existing country rocks, the main mass of melt forming a pool at the base of the crater. The lithostatic load of accumulating fall-back

breccia was considered to have forced the melt upward, mainly along the basal breccia/grey Onaping contact, and where it reached surface, the melt may have overflowed and acted as a lava flow.

Peredery (1972a) described the distribution of shock-metamorphic features in the Onaping Formation, and also described 4 varieties of devitrified and recrystallized glass fragments which are found within it. He noted that 2 or more varieties commonly occur side by side throughout the formation. Electron microprobe analyses of 1 of the types of glass, termed fluidal glass, showed it to be chemically heterogeneous in any 1 fragment, and heterogeneous from fragment to fragment. The composition of different glass fragments ranges from alkali-rhyolite to alkali-trachyte to trachyte to latite, to nepheline alkali-trachyte to phonolite. Peredery (1972a) pointed out that the glasses are anomalous in composition, and that the compositional distribution field is unlike that found at a conventional volcano. It was suggested that certain types of glass represent molten or partially fused basement rocks of various types, while other types represent basement rocks shocked to glass in their solid state.

Card and Hutchinson (1972) reviewed the regional geological setting of the Sudbury Structure. These authors pointed out that both the location and shape of the Sudbury Structure are closely related to tectonic features, including the junction of 3 structural provinces and 2 main fault systems; that it lies within a possible major Precambrian rift system; and that the Sudbury Igneous Complex is only 1 of a series of varied mafic intrusions, many with associated nickel-copper mineralization, that occur in this rift system. Card and Hutchinson (1972) suggested that the evidence strongly indicates that the Sudbury Structure is an integral part of a prolonged geologic evolution, in which tectonics, stratigraphy, petrogenesis, and ore genesis are all interrelated.

Card (1978) reviewed the geology of the Sudbury-Manitoulin area, and summarized in this report his work of several years in the area. He discussed the origin of the Sudbury Structure, reviewed the arguments for and against impact, and summarized his view (Card 1978, p. 195-196) as follows:

Evidence for a meteorite impact includes the following: the probable original circular shape of the structure; the nature of the Onaping Formation which is similar to suevite breccias of known meteorite impact sites, the abundant Sudbury breccias and shatter cones; and the microscopic evidence for shock metamorphism. Arguments against a meteorite impact origin include the following: the relationships of the Sudbury Structure to major tectonic elements such as the Grenville Front; to major structures, such as faults of the Murray and Onaping Systems; to magnetic-gravity anomalies indicative of larger scale crustal peculiarities;

to pronounced facies variations in the adjacent Huronian rocks; and to regional orogenic events. These relationships indicate that the Sudbury Structure is an integral part of its regional setting in space and time, and is not simply the product of fortuitous meteorite impact at this particular site.

The Creighton Pluton was described by Dutch (1979a). The paper was discussed by Card (1979), followed by further comments by Dutch (1979b).

Numerous geochronologic studies have been carried out in the area. The principal studies have been by Fairbairn *et al.* (1960, 1965, 1968, 1969), Faure *et al.* (1964), Ulrych and Russell (1964), Souch, Podolsky *et al.* (1969), Fullagar *et al.* (1971), Gibbins *et al.* (1972), Hurst and Wetherill (1974), Gibbins and McNutt (1975a, 1975b), Hurst and Farhat (1977), Krogh *et al.* (1982), and by Frarey *et al.* (1982). In addition, numerous age determinations have been made as part of an ongoing study by the Geological Survey of Canada, chiefly by Wanless and his co-workers; the results are summarized in Stockwell (1982).

Results of studies published prior to 1982 were based very largely on the Rb/Sr and K/Ar methods, involving both mineral and whole rock ages. Gibbins and McNutt (1975a) summarized results of earlier work on the Sudbury Igneous Complex, and based on their Rb/Sr whole rock data concluded that the Complex was intruded and crystallized at 1956 ± 98 Ma. These authors also concluded that the Murray Granite (Murray Pluton) is older than the Sudbury Igneous Complex, dating it at 2260 Ma. In a subsequent paper, Gibbins and McNutt (1975b) discussed Rb/Sr ages and polymetamorphism at Sudbury and they concluded that consistent Rb/Sr ages, calculated using mineral-whole rock pairs, confirmed the Sudbury Event (i.e. shock metamorphism, formation of Sudbury Breccia, intrusion of the Sudbury Igneous Complex) occurred at 1900 Ma; the Penokean (Hudsonian) Orogeny at 1600 to 1800 Ma; a cryptic (Elsonian) thermal event at 1300 to 1450 Ma; and the Grenville Orogeny at 900 to 1200 Ma.

Hurst and Farhat (1972) found that norite whole rock Rb/Sr data gave an age of 1883 ± 136 Ma, while the micropegmatite (granophyre) Rb/Sr system has been disturbed and does not yield an isochron. Rb/Sr studies of Superior Province granites north of Sudbury yield an age of 2698 ± 162 Ma. U/Pb zircon studies of these granites, and of granitic clasts in Sudbury Breccia northwest of the Sudbury Igneous Complex, gave an age of 2.71 ± 0.05 Ga, suggesting that the granitic clasts in the breccia in this area were derived from the Superior Province granites. Hurst and Farhat (1977) also noted that granitic rocks 150 km north of Sudbury have been undisturbed for about 2.6 Ga based on Rb/Sr mineral studies, while granites, Sudbury Breccia, and norite at the edge of the Sudbury Igneous Complex

have been disturbed by the Penokean Orogeny 1.7 to 1.75 Ga ago.

Using the U/Pb zircon method, Krogh *et al.* (1982) dated the felsic norite of the North Range at $1849.6 \pm 3.4/-3.0$ Ma, and black norite of the South Range at $1849.4 \pm 1.9/-1.8$ Ma. Frarey *et al.* (1982), also using the U/Pb zircon method, obtained a date on zircon from the Creighton Granite of $2333 \pm 33/-22$ Ma, which they interpreted as being the time of magmatic intrusion of the Creighton and Murray Granites.

While much of the literature on Sudbury geology has understandably concentrated on the economically important Sudbury Igneous Complex and the ores, rocks of the Sudbury Basin have received considerable attention in recent years. The work of Thomson (1956), Williams (1956), Fullagar *et al.* (1971), Stevenson (1972), and of Peredery (1972a, 1972b) has been noted earlier. Desborough and Larson (1970) described nickel-bearing iron sulphides from the Onaping Formation. Rousell (1972) presented a detailed description of the Chelmsford Formation, classifying it as a proximal turbidite, derived from a tonalitic terrain. Cantin and Walker (1972) examined paleocurrent directions and lateral facies changes in the Chelmsford Formation, concluding that the Sudbury Basin was not circular, but elongate during its deposition. Beales and Lozej (1975) suggested that the rocks of the Whitewater Group resemble the succession of beds to be expected for sediments accumulated in a large impact-generated crater. They followed some earlier writers in classifying the lower Onaping Formation as a fall-back breccia; suggested the upper Onaping Formation and the overlying Onwatin Formation represent a restricted crater series of sediments, and further suggested that the succeeding Chelmsford Formation represents an open marine turbidite sequence deposited when the crater rim no longer influenced sea bottom current circulation. The Whitewater Group is preserved only within the Sudbury Basin, which they attributed to preferential preservation due to compaction-generated subsidence over the crater and impact-fractured area.

Although all government reports and many papers in journals describe aspects of the structural geology of the area, only a few papers concern the structural geology in their entirety. Brocoum and Dalziel (1974) described the structural geology of the area, concluding that finite-strain analysis of deformed concretions within the Chelmsford Formation of the Sudbury Basin suggested that the Basin was originally almost circular in outline. Rousell (1975) studied foliation and lineation in the Onaping Formation, and concluded that prior to deformation the Sudbury Basin was less elliptical than its present form in plan view, but that it is unlikely that it was ever circular. Rousell (1976) described crystallographic orientation of quartz

from the basal quartzite breccia of the Onaping Formation; kink bands in the Onaping Formation (Rousell 1980); and mineralization in the Whitewater Group (Rousell 1982). Jointing in the Sudbury Basin was described by Rousell and Everitt (1981).

The mineralogy and chemistry of the ores have been discussed in many papers, most notably those of Hawley (1962, 1965). Several more recent papers deal with aspects of the chemistry of the ores and of the Sudbury Igneous Complex.

Pyrrhotites from the Strathcona Mine were studied by Vaughan *et al.* (1971). Gasparrini and Naldrett (1972) showed that systematic chemical variations in the opaque oxides of the Sudbury Igneous Complex resemble those of other differentiated layered intrusions, supporting the earlier findings of cryptic variation. Duke and Naldrett (1976) discussed the sulphide mineralogy of the Main Mass. Rare earth elements of the norite, oxide-rich gabbro, and granophyre were studied by Kuo and Crocket (1979), who concluded that the rocks are comagmatic and that they are related to each other by gravitational fractional crystallization processes.

Keys and Crocket (1970), and Chyi and Crocket (1976) described the distribution of precious metals in Sudbury ores. General aspects of the composition of nickel sulphides with particular reference to their content of platinum group elements and gold, with some references to Sudbury ores, were discussed by Naldrett *et al.* (1979). Hoffman *et al.* (1979) described the noble metal content of ore from the Levack West (since re-named McCreedy West) and Little Stobie Mines. Platinum metals in magmatic sulphide ores were discussed by Naldrett and Duke (1980). Naldrett *et al.* (1982) described compositional variations within and between 5 Sudbury ore deposits, with particular emphasis on the concentration of platinum group elements and gold. Naldrett *et al.* (1982) concluded that the marked compositional variation across 2 deposits on the North Range is due to progressive fractional crystallization of monosulphide solid solution from sulphide melt, with the residual liquid being expelled progressively into the Footwall.

Paleomagnetism of the Sudbury Igneous Complex has been studied by Hood (1961), Sopher (1963), Larochelle (1969), and Morris (1980, 1981, 1982). The studies of Hood, Sopher, and Larochelle showed a marked angular discordance between North and South Range remanence directions. No significant directional differences were found between sites in the norite and granophyre. The evidence was interpreted as indicative of post-intrusion tectonic activity. The work of Gasparrini and Naldrett (1972) showed that magnetites from the South Range norite had equilibrated at extremely low temperatures, below 600°C, suggestive of a late reheating event which would make

it meaningless to compare remanence directions of the North and South Ranges. Irving and Lapointe (1975) suggested an alternative method of defining rotation of the North Range, but interpretation of the South Range data remained speculative.

Morris studied paleomagnetic features of the norite, granophyre, and offsets (1980, 1981, 1982, respectively) and concluded that noritic magma, which differentiated to form the norite and plagioclase-rich phase of the granophyre was intruded into an open syncline plunging gently to the southwest. Subsequent folding produced an approximately symmetrical basin. He suggested that the South and East Ranges were then metamorphosed and folded to steeper angles; that the basin was subsequently crosscut by a series of major faults; and the South and East Ranges were rotated relative to the rest of the basin. Work on the granophyre suggested that the granophyre-rich phase was intruded into the plagioclase-rich granophyre, perhaps contemporaneously with some transbasin faulting. He noted that the "pepper-and-salt micropegmatite" (granophyre) may represent a third intrusive event. His work on the offsets (Morris 1982) suggested that they evolved magmatically and tectonically as integral components of the Sudbury Igneous Complex, having been formed by a series of separate magmatic pulses in the same sequence as the main Complex and having undergone the same tectonic evolution. He also stated that 3 distinct periods of sulphide genesis were common to all the offsets and to the remainder of the Sudbury Igneous Complex: the first phase was believed to be of probable magmatic origin and to have been introduced with the granophyre-rich phase. The other 2 phases may represent remobilization and redeposition of pre-existing deposits, of hydrothermal introduction of new generations of sulphide.

In other paleomagnetic work in the area, Larochelle (1967) and Palmer *et al.* (1977) studied the paleomagnetism of the Sudbury diabase dike swarm, and Schwarz (1977) investigated the depth of burial of the norite at the time of intrusion of the dike swarm (1250 Ma). Results of the latter study suggested that erosion has subsequently removed a 7 km thick layer from the area.

Regional geophysical characteristics of the Sudbury area have been measured by magnetic, radiometric, and gravity surveys. Aeromagnetic survey data have been published at a scale of 1:250 000 (ODM-GSC 1965). Schwarz (1973) investigated the magnetic characteristics of several Sudbury orebodies and commented on their aeromagnetic expressions. Airborne gamma-ray spectrometric maps (at a scale of 1:250 000) and flight-line profiles were published in 1978 (OGS 1978). Gravity surveys have been carried out by Miller and Innes (1955), Popelar (1971, 1972), and Gupta (1981, 1983).

CHAPTER 1

While there is considerable controversy over the proposed Precambrian meteorite impact origin for the Sudbury Structure approximately 1850 Ma ago, there is little controversy over a much younger, Tertiary, impact origin for the Lake Wanapitei basin which lies on the eastern side of the Sudbury Structure.

Dence and Popelar (1972) described evidence for an impact origin of the Late Wanapitei basin, and included microscopic evidence of shock metamorphism in their study. Coesite from the area was described by Dence *et al.* (1974) and considered by them as additional evidence supporting a hypervelocity impact origin. Isotopic studies of shock-metamorphosed rocks and shock-produced melt glasses from the Lake Wanapitei Structure were reported by Winzer *et al.* (1976), who concluded from K/Ar dating that the impact event occurred 37 Ma ago. Impact melt rocks from the structure were described by Wolf *et al.* (1980). Allen *et al.* (1982) examined alteration minerals in breccia from the Lake Wanapitei Structure and from the Onaping Formation.

Stevenson (1979) presented an extensive review of the history of geological work and of geological concepts developed in the Precambrian of Sudbury up to the time of publication.

Fleet (1979) proposed that the shatter cones of the area originated through tectonic activity rather than through meteorite impact. His arguments were refuted by Pattison (1980), but his original suggestion was resented by Fleet (1980).

The origin of the Sudbury Structure in the light of the meteorite impact theory was reviewed and criticized by Stevenson and Stevenson (1980), and the paper was responded to in a discussion by Rousell (1981).

Frape and Fritz (1982) studied the chemistry and isotopic composition of saline groundwaters from several mines and wells in the area.

The Quaternary geology of the Sudbury area was mapped in detail and described by Burwasser (1979).

In recent years, the Ontario Geological Survey has carried out both special studies and systematic geological mapping in the area.

The Sublayer and adjacent Footwall rocks have been investigated by Dressler (1979, 1980a, 1981b, 1982), and the Onaping Formation has been studied by Muir (1982). A map of the Sudbury area at a scale of 1:50 000, incorporating recent published and unpublished data, was compiled by Dressler (1984).

Geological mapping at a scale of 1 inch to ¼ mile on the North and East Ranges was carried out by Muir (1979, 1981, 1983), Dressler (1980b, 1981a), Lafleur (1981) and Lafleur *et al.* (1982a, 1982b, 1982c), while on the South Range, recent geological mapping has

been carried out by Innes (1978), Giblin (1982), and Martins (1983).

It is intriguing to note that after nearly a century of geological work, significant new information continues to emerge. The Manchester Offset was first recognized as recently as the early 1970s, first appeared on a published map in 1981 (Adlington 1981), and is described for the first time in this volume (Grant and Bite 1984, Chapter 12, this volume).

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CHAPTER 2

The Sudbury Structure: Its Regional Geological and Geophysical Setting

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ABSTRACT

Archean and Proterozoic rocks of the Superior, Southern, and Grenville Provinces of the Canadian Shield come together near the Sudbury Structure, a unique Proterozoic feature consisting of mafic and felsic intrusions called the Sudbury Igneous Complex, breccia and sediments of the Whitewater Group inside this complex, and brecciated, shatter-coned country rocks without. Formation of this structure, variously attributed to meteorite impact or explosive volcanism, occurred about 1850 Ma ago. The Superior Province to the north consists of Late Archean supracrustal, plutonic, and gneissic rocks, as well as granulites. Gravity and magnetic models indicate that the supracrustal rocks ("greenstone" belts) and granite plutons generally extend to depths of < 6 km, whereas the granulite terrains may represent exposures of middle or lower crust. The Southern Province, consisting of Proterozoic sedimentary rocks, volcanic rocks, and mafic and felsic intrusions, has a number of gravity and magnetic anomalies. Positive magnetic anomalies in the Manitoulin Island area are attributed to 1500 Ma old plutons. An intense magnetic low over the axis of the Huronian Basin may be due to basement shearing and alteration along a major structural zone, the Great Lakes Tectonic Zone. An intense magnetic anomaly near Lake Temagami is attributed to magnetite-rich intrusions at depths of several km. The Sudbury gravity-magnetic anomaly, like the Temagami anomaly, occurs along a linear zone of gravity and magnetic anomalies that extend some 350 km from Elliot Lake to Englehart, Ontario.

INTRODUCTION

The Early Proterozoic Sudbury Structure of the Canadian Shield, in addition to having one of the world's most significant concentrations of base-metal sulphide ores, is one of geology's great enigmas. The genesis of the elliptical Sudbury Igneous Complex and its sulphide ores, the rocks of the Whitewater Group within the intrusion, and the collar of brecciated Archean and Proterozoic rocks about the intrusion have been vigorously debated for many years (for example, Guy-Bray 1972). On one hand, the presence of abundant shock metamorphic textures and structures indicates that meteorite impact played an important role in

the formation of this structure (Dietz 1964; French 1970). On the other hand, Card and Hutchinson (1972) argued that Sudbury shows special relationships in space and time to major geological elements and events; some of these pre-date the structure by many millions of years. Therefore, the Sudbury Structure may have originated from endogenic rather than exogenic processes.

Any theory of origin for the Sudbury Structure must take into account its setting in space and time. In this article, we shall examine Sudbury in relation to the major geological-geophysical features and evolution of this part of the Precambrian Shield. We will describe the rocks and structures of the Archean Superior Province north of Sudbury, the development and evolution of the Early Proterozoic volcano-sedimentary basins of the Southern Province, and the gneissic terrain of the Grenville Province south of Sudbury. We will attempt to deduce the deeper crustal structure on a regional basis and at Sudbury by modelling gravity and aeromagnetic data. The basic aim will be to describe and interpret the geological and geophysical character of this part of the Canadian Shield in order to ascertain the place of the Sudbury Structure within its framework.

REGIONAL GEOLOGY

The Sudbury Structure is located in the southern Canadian Shield in the eastern part of the Southern Province (Figure 2.1). It straddles the main contact between the Early Proterozoic Huronian supracrustal rocks of the Southern Province and the Archean plutonic rocks of the Superior Province. The Sudbury Structure lies some 10 km north of the Grenville Front, the northern limit of the Grenville Province. The Sudbury Igneous Complex, a major component of the structure, was emplaced about 1850 Ma ago, as is demonstrated by the U-Pb zircon age of the norite (Krogh *et al.* 1982a).

Superior Province

Archean rocks of the Superior Province north of Sudbury can be described in terms of several major lithostratigraphic components which include "greenstone" belts, metasedimentary belts, felsic plutons, and gneissic terrains including granulites (Card 1979). East-trending volcanic-rich and sediment-rich belts or subprovinces alternate with each other. A northeast-trending zone of high-grade gneiss

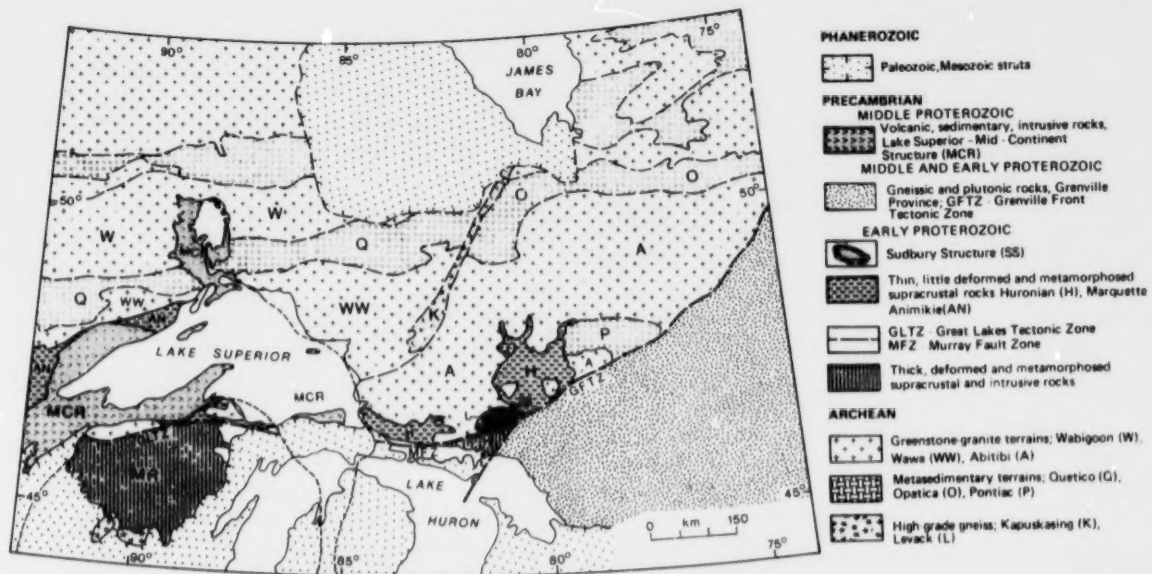


Figure 2.1. Major geological elements of the Southern Part of the Canadian Precambrian Shield.

traverses the east-trending subprovinces (Figure 2.1). In addition to different rock assemblages, the subprovinces also have distinctive structural trends and styles, metamorphic grades, isotopic ages, and geophysical characteristics (Percival and Card 1983).

GRANITE-"GREENSTONE" AND METASEDIMENTARY SUBPROVINCES

The volcanic-rich terrains, the Wabigoon, Wawa, and Abitibi Subprovinces, are characterized by sinuous "greenstone" belts, upright folds and domal structures, and low- to medium-grade metamorphism. The English River, Quetico, and Pontiac Subprovinces have dominantly metasedimentary supracrustal rocks (mainly a turbiditic wacke protolith), linear structural patterns, subvertical to subhorizontal structures, and marginal low-grade to internal high-grade (migmatite zone) metamorphic assemblages. Plutonic rocks include: early synvolcanic ultramafic to felsic (commonly quartz diorite to granodiorite) intrusions; younger, commonly syntectonic to late tectonic granodioritic intrusions; and still younger, commonly massive granodioritic, granitic, and syenitic plutons (Card 1982). Much of the Archean of the Abitibi Subprovince north of Sudbury consists of massive felsic plutons, the Algonian plutons (AG, Figure 2.2). These intrude tonalite-granodiorite gneiss characterized by numerous layers and inclusions of amphibolite and mafic gneiss. The tonalitic component of the gneiss is

considered to be mainly of plutonic origin, whereas much of the mafic material is probably of supracrustal (volcanic) origin (Card 1979).

A time framework for events in the Abitibi Subprovince can be constructed from U-Pb zircon dates on volcanic and plutonic rocks. In the western Abitibi Subprovince, volcanic rocks range in age from 2725 Ma to 2703 Ma (Nunes and Pyke 1980; Nunes and Jensen 1980). Early, synvolcanic plutons yield age dates in the range 2744 Ma to 2707 Ma (Krogh and Davis 1971; Percival and Krogh 1983). A number of late- to post-tectonic plutons have zircon dates of about 2680 Ma (Krogh *et al.* 1982b; Percival and Krogh 1983). These dates bracket the age of major post-volcanic deformation and metamorphism in this part of Superior Province between 2700 Ma and 2680 Ma, and show that major volcanic, plutonic, and tectonic events were of relatively brief duration, and were essentially synchronous throughout the Abitibi Subprovince, a region some 800 km long and 200 km wide.

HIGH-GRADE GNEISS TERRAINS

The most prominent high-grade gneiss terrain of the central Superior Province is the Kapuskasing Zone (K, Figure 2.1). This zone is a narrow, northeast-trending belt of high-grade gneiss that transects the east-trending subprovinces, and is characterized by positive aeromagnetic and gravity anomalies (Thurston *et al.* 1977). The rocks include paragneiss, mafic gneiss, gneissic and xenolithic tonalite, and the Shawmere

Layered Anorthosite-Gabbro-Tonalite Complex, that have been deformed and metamorphosed under upper amphibolite to granulite facies conditions. The eastern contact of the high-grade Kapuskasing Zone with the low-grade Abitibi Subprovince is a fault, whereas westward there is a complex gradation from high-grade gneiss of the Kapuskasing Zone to low-grade rocks of the Michipicoten "Greenstone" Belt near Lake Superior. This 120 km wide transition zone is considered to represent an oblique section through some 20 km of Archean crust, uplifted along a major northwest-dipping thrust fault (Percival and Card 1983).

The supracrustal rocks of the Kapuskasing Zone, presently high-grade gneiss, were deposited prior to 2765 Ma, the minimum U-Pb zircon age of tonalite of the Shawmere Complex (Percival and Krogh 1983). Consequently, these rocks are older than any supracrustal rocks yet found in the neighbouring Abitibi Subprovince. Conversely, metamorphic zircons from the Kapuskasing gneiss yield U-Pb ages of 2650 to 2627 Ma, demonstrating that high temperature conditions persisted in these rocks, presumably at depth, long after stabilization of the Abitibi Subprovince. Uplift of the Kapuskasing rocks probably occurred in the late Archean and Proterozoic in response to orogenic events in other parts of the Shield.

The Levack Gneiss Complex (L, Figures 2.1 and 2.2), a terrain with many similarities to the Kapuskasing Structural Zone, is in contact with the North Range of the Sudbury Igneous Complex and constitutes part of the Archean basement beneath the northern half of the Sudbury Structure. Rocks of the Levack Gneiss Complex include migmatitic tonalitic gneiss (quartz diorite to granodiorite), with abundant, locally dominant mafic layers and xenoliths and migmatitic paragneiss; metamorphosed to upper amphibolite and lower granulite facies. In addition, there are foliated tonalitic and granodioritic intrusions of possible anatectic origin, as well as mafic, ultramafic, and anorthositic intrusions. The gneisses were intruded and extensively retrograded by: younger, post-tectonic Algonian granites, late Archean and Middle Proterozoic mafic dikes, and veins and irregular masses of Sudbury Breccia. The Levack Gneiss, like that of the Kapuskasing Zone, may represent older (Middle Archean?) supracrustal and plutonic rocks brought to surface near the southern margin of the Superior craton by faulting or doming. The age of uplift is not known with certainty. The presence of Sudbury Breccia (pseudotachylite) in the Levack Gneiss demonstrates that uplift occurred before the Sudbury Event. The lack of deformation and metamorphism of Late Archean Matachewan dikes and Algonian Granite that intrude the gneiss indicate that uplift occurred before or during emplacement of

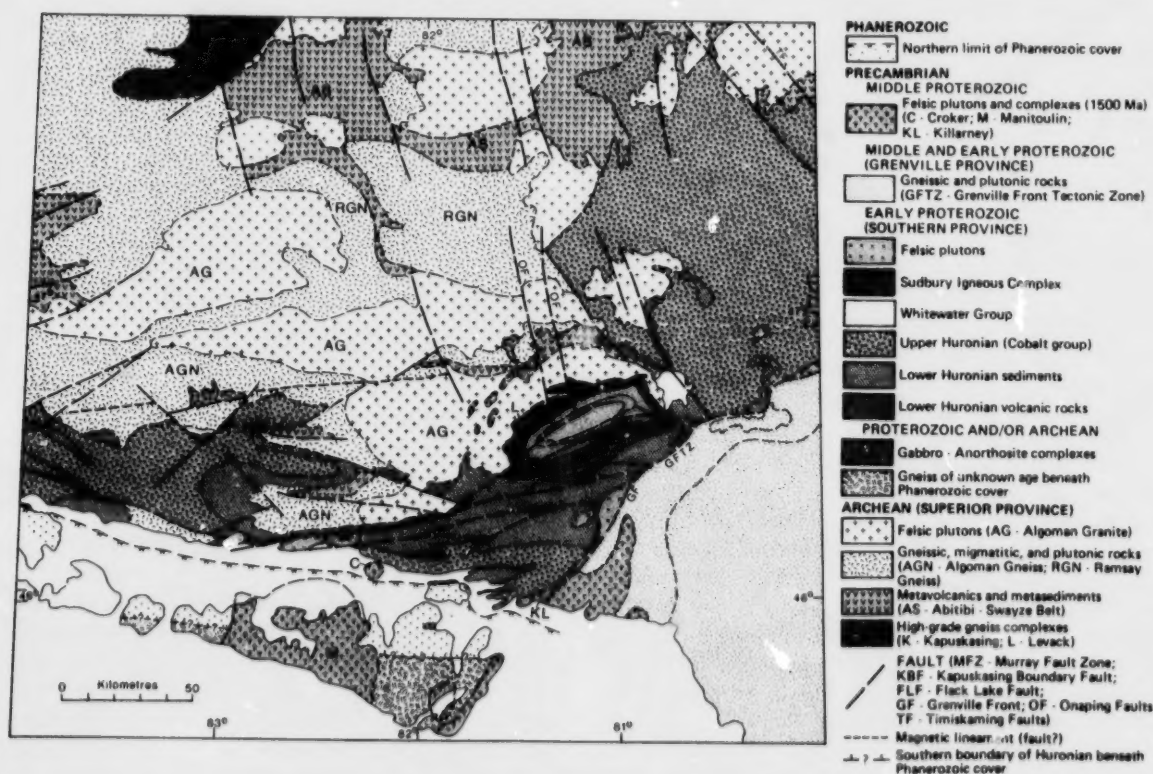


Figure 2.2. General geology of the Sudbury region.

these intrusions some 650 to 800 Ma before the formation of the Sudbury Structure. The Levack Gneiss Complex may have constituted the core of a major domal structure upon which the Sudbury Structure was later superimposed.

In summary, the heterogeneous collage of supracrustal and plutonic rock units that constitutes the Superior Province (mainly of Late Archean age) was assembled to form a stable craton by the end of Late Archean time. Renewed tectonic activity in the Early Proterozoic, controlled in part by previously established structural elements, led to the development of the Southern Province depositional basin along the southern flank of the Superior craton.

Southern Province

Early Proterozoic supracrustal sequences of the Southern Province, the Huronian Supergroup (H, Figure 2.1) in the east and the Marquette Range Supergroup (MR, Figure 2.1), Animikie Group (AN, Figure 2.1), and correlative rocks in the west, form a discontinuous linear fold belt some 1300 km long along the southern margin of the Superior Province (Card *et al.* 1972). The sequences were deposited between 2500

Ma and 1900 Ma ago (Van Schmus 1976), and consist mainly of clastic sedimentary and volcanic rocks with subordinate chemical sedimentary rocks, chiefly iron formation. These sequences thicken southward from an erosional edge to a maximum of more than 10 km (Figure 2.3). The clastic sedimentary rocks were derived mainly from the Superior Province Archean craton to the north.

HURONIAN SUPERGROUP

The Huronian Supergroup was deposited between 2100 Ma ago, the age of the Nipissing Diabase, and about 2500 Ma ago, the minimum age of Archean basement granites. The lowermost Huronian volcanic units in the Sudbury area are older than 2333 Ma, the age of the intrusive Creighton granite (Frarey *et al.* 1982). Recent U-Pb zircon age determinations on rhyolite of the Huronian Copper Cliff Formation indicate that it is 2460 ± 20 Ma old (T.E. Krogh, Geochronologist, Royal Ontario Museum, personal communication, 1983).

The Huronian Supergroup consists mainly of clastic sedimentary rocks with local basal volcanic accumulations. The succession displays southward and

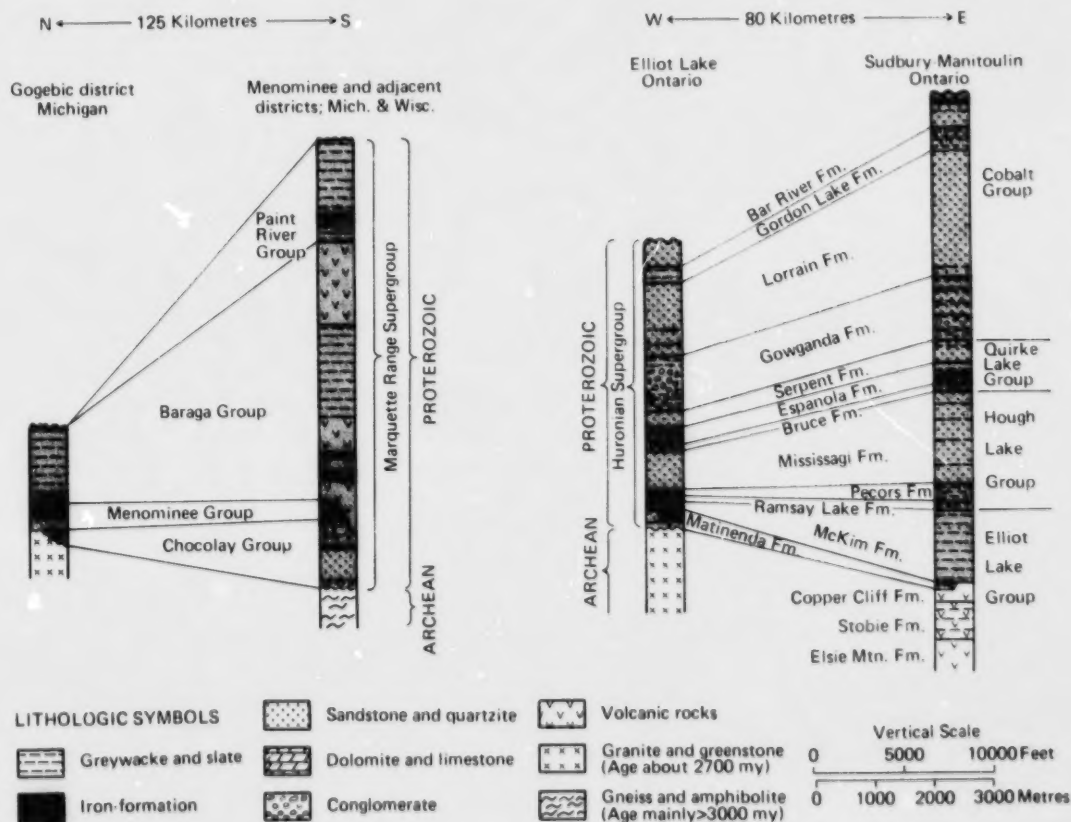


Figure 2.3. Stratigraphy of the Huronian and Marquette Range Supergroups (after Sims *et al.* 1981).

eastward variations in thickness and facies that are most marked across major east-trending faults of the Murray System. The Elliot Lake Group, the basal unit, is a heterogeneous assemblage of sedimentary and volcanic rocks. In the East Bull Lake and Dunlop Township areas, there are layered gabbro-anorthosite intrusions that are probably genetically related to the Huronian volcanic accumulations. Recent U-Pb zircon age determinations on the East Bull Lake Gabbro-Anorthosite Intrusion indicate that it is about 2480 Ma old (T. Krogh, Geochronologist, Royal Ontario Museum, personal communication, 1984) or approximately the same age as Huronian volcanic rocks next to Sudbury. In the northwest, in the Sault Ste. Marie and Elliot Lake areas, the group is about 600 m thick and consists of arkose, quartz-pebble conglomerate, and local, thin, subaerial volcanic accumulations, composed chiefly of tholeiitic and slightly alkalic basalts. In the northeast, the Elliot Lake Group apparently, is absent. In the southeast, near Sudbury, the group consists of several thousand metres of tholeiitic pillow basalt and rhyolite and several thousand metres of greywacke and siltstone of the McKim Formation. The McKim Formation near Sudbury is a thick sequence of mainly thick-bedded wacke with well-developed Bouma cycles. The McKim Formation thins westward and northward where it consists mainly of thin-bedded siltstones and pelites.

The overlying Hough Lake and Quirke Lake Groups constitute 2 major sedimentary cycles, each comprising a lower conglomeratic unit, a middle wacke-siltstone unit, and an upper crossbedded sandstone unit. Both groups thicken from a maximum of about 1500 m in the northwest to over 6000 m in the southeast. The upper half of the Huronian Supergroup, the Cobalt Group, is much more areally extensive than the lower half and consists of a heterogeneous assemblage of conglomerate, siltstone, wacke, and arkose (Gowganda Formation); a thick succession of arkose and orthoquartzite (Lorrain Formation); a thin unit of varicoloured siltstone and sandstone (Gordon Lake Formation); and an upper unit of orthoquartzite and hematitic siltstone (Bar River Formation). The preserved Cobalt Group has a maximum thickness of about 3500 m in the Elliot Lake area and 5000 m in the Sudbury-Manitoulin area.

The rocks of the Huronian Supergroup were deposited under fluvial, deltaic, and shallow marine conditions. The sedimentary cycles of the lower Huronian Supergroup may represent regressive depositional cycles controlled by syndepositional faulting and differential movements on basement blocks. Each cycle began with normal faulting and subsidence that triggered debris flows resulting in deposition of the conglomerate units. This was followed by wacke and siltstone, deposited in part by turbidity currents under relatively deep-water conditions, and in part under

deltaic conditions. As basin infilling brought about a return to shallow water and emergent conditions, the crossbedded sandstone units were deposited. The Cobalt Group is an extensive blanket of coarse-grained clastic debris grading upward into shallow-water sandstone. Evidence exists that rocks of the Gowganda Formation were deposited by glacial and glacially-related processes (Young 1970).

MARQUETTE RANGE AND ANIMIKIE GROUPS

Early Proterozoic sedimentary and volcanic rocks of the Marquette Range Supergroup and the Animikie Group were deposited some 2200 to 1900 Ma ago (Goldich 1973). These sequences are considered to be younger than the Huronian, with the possible exception of the basal formation in northern Michigan. The Marquette Range and Animikie sequences form a southward-thickening wedge of clastic and chemical sedimentary rocks and mafic-felsic volcanic rocks. In the north, these successions are thin (1500 to 2000 m) and dominantly sedimentary; in the south, they are notably thicker (up to 9000 m), and consist of interbedded volcanic rocks and sedimentary rocks. There are abrupt thickness and facies variations from place to place indicating deposition in localized, fault-controlled basins (Morey 1973; Cannon 1973).

The Marquette Range Supergroup and Animikie Group rocks represent several major depositional cycles separated by unconformities. Each cycle begins with quartz sandstone and/or conglomerate, followed by stromatolitic dolomite, iron formation, and slate. The uppermost cycle of the Marquette Range Supergroup, the Baraga Group, marks a period of pronounced disturbance with mafic and felsic volcanism and widespread subsidence that culminated in deposition of thick greywacke turbidites in the south. The deposition of wacke and shale forming the upper part of the Animikie Group in the north indicates foundering occurred here as well.

Depositional patterns in the Early Proterozoic sequences of the Lake Superior region reflect increasing crustal instability and southward-prograding differential downwarping. The facies variations record a transition in space and time from a stable craton to an unstable, deep-water environment. Young (1982) has tentatively correlated the upper part of the Huronian sequence with the lower part (Chocoma Group) of the Marquette Range Supergroup and the upper part of the Marquette Range Supergroup and Animikie Group with the Whitewater Group of the Sudbury Basin. He recognized 4 main stages in the evolution of the Southern Province depositional basins. During an initial graben stage, lower Huronian volcanic and sedimentary rocks were deposited in fault-controlled basins or troughs by southeast- to south-flowing paleocurrents.

This was followed by regional subsidence and deposition of the upper Huronian and lower Marquette Range sedimentary rocks over a broad area. Uplift, mainly in the east, led to a restricted depositional phase in the west and the development of the Superior-type iron formations. Finally, a flysch phase was brought about by widespread foundering and deposition of a blanket of turbidites (the Virginia, Rove, Michigamme, Chelmsford Formations, for example) throughout the entire region.

DEFORMATION, METAMORPHISM, AND PLUTONISM

Throughout the Southern Province, deposition essentially ended with the initiation of a protracted series of orogenic events. In the east, evidence exists for the early deformation of the Huronian rocks, possibly before they were fully lithified. Card (1978a) and Young (1982) have described ragged, slumped contacts along early faults and the presence of major slump blocks. Field evidence indicates that deformation of the lower Huronian rocks occurred prior to deposition of the Gowganda Formation. Major folds were formed before intrusion of the Nipissing Diabase at 2100 Ma be-

cause Nipissing intrusions transect the axial surfaces of some major folds. Following the intrusion of the Nipissing Diabase, but before emplacement of the Sudbury Igneous Complex there was a metamorphic event that produced subgreenschist to lower amphibolite assemblages (Card 1978b). Rubidium-strontium isotopic studies of Huronian metasediments indicate that this metamorphism occurred about 1900 ± 50 Ma ago (Fairbairn *et al.* 1969). Following emplacement of the Sudbury Igneous Complex, at 1849 Ma, there was further deformation and low grade (retrograde) metamorphism, emplacement of granite plutons (Cutler, Chief Lake, Eden Lake Plutons) in the south about 1750 ± 50 Ma ago, and finally intrusion of anorogenic plutonic complexes (Killarney, Croker, Manitoulin Island Plutons) about 1500 Ma ago (Table 2.1).

In the Lake Superior region, major deformation, metamorphism, and plutonism occurred during the Penokean Orogeny about 1850 ± 50 Ma ago. This was followed by rhyolitic volcanism and coeval granitic intrusions about 1760 Ma ago, and finally by emplacement of anorogenic plutons (Wolf River Batholith) about 1500 Ma ago (Van Schmus 1976; Van Schmus *et al.* 1975). The major pre- and post-Sudbury Igneous

TABLE 2.1: PRECAMBRIAN ROCK UNITS AND EVENTS IN THE SUDBURY REGION.

Event	Rock Unit	Approximate Age (Ma)
PRECAMBRIAN		
Middle Proterozoic		
Grenville Orogeny		1000-1200
Mafic intrusion	Sudbury diabase dikes	1250
Felsic intrusion	Croker, Manitoulin Island, Killarney Complexes	1500
Early Proterozoic		
Deformation and metamorphism	Cutler, Grenville Front plutons	1750 ± 50
	Sudbury Igneous Complex	1849
	Whitewater Group	
Sudbury Event	Breccia, shatter cones	
Metamorphism and deformation (Penokean)		1850-1900
Mafic intrusion	Nipissing Diabase	2100
Felsic intrusion	Creighton, Murray Granites	2333
Early deformation, faulting, basin subsidence, volcanism and sedimentation	Huronian Supergroup	2460
	Unconformity	
Archean		
Mafic intrusion	Matachewan dikes	2630
Felsic intrusion	Algoman granite	
	Granodiorite suite intrusions	2680
Deformation and metamorphism		
Volcanism	Abitibi Subprovince volcanic rocks and sediments	2700-2750
	Levack Gneiss	

CHAPTER 2

Complex events which occurred at about 1850 to 1900 Ma and 1750 Ma were essentially synchronous throughout the Southern Province.

PATTERNS OF DEPOSITION AND TECTONISM

The Early Proterozoic rocks of the Southern Province display distinctive asymmetrical patterns of volcanism, sedimentation, deformation, metamorphism, and plutonic activity (Sims *et al.* 1981). In the northern parts of their outcrop areas, the Huronian, Marquette Range, and Animikie sequences rest unconformably on a Superior Province Archean basement that remained relatively stable throughout the depositional and subsequent orogenic history. Consequently, these northern sequences are thin, dominantly sedimentary, and have been little deformed or metamorphosed (Fig-

ure 2.4). Proterozoic felsic plutons are absent. In contrast, in the south, the Early Proterozoic sequences were deposited on Archean gneissic basement or on basement of unknown character. These sequences are thick, contain a high proportion of volcanic rocks, and are deformed, metamorphosed, and intruded by felsic plutons.

The boundary between these contrasting Archean and Early Proterozoic terrains coincides with a zone of faulting and dislocation, the Great Lakes Tectonic Zone (GLTZ)-Murray Fault (MFZ) System (Figure 2.1; Sims *et al.* 1980). This zone is a major, long-lived crustal structure that controlled patterns of deposition of Early Proterozoic supracrustal rocks some 1900 to 2500 Ma ago, and subsequent orogenic activity some 1700 to 1900 Ma ago. It is also the approximate northern limit of 1500 Ma old plutonic and

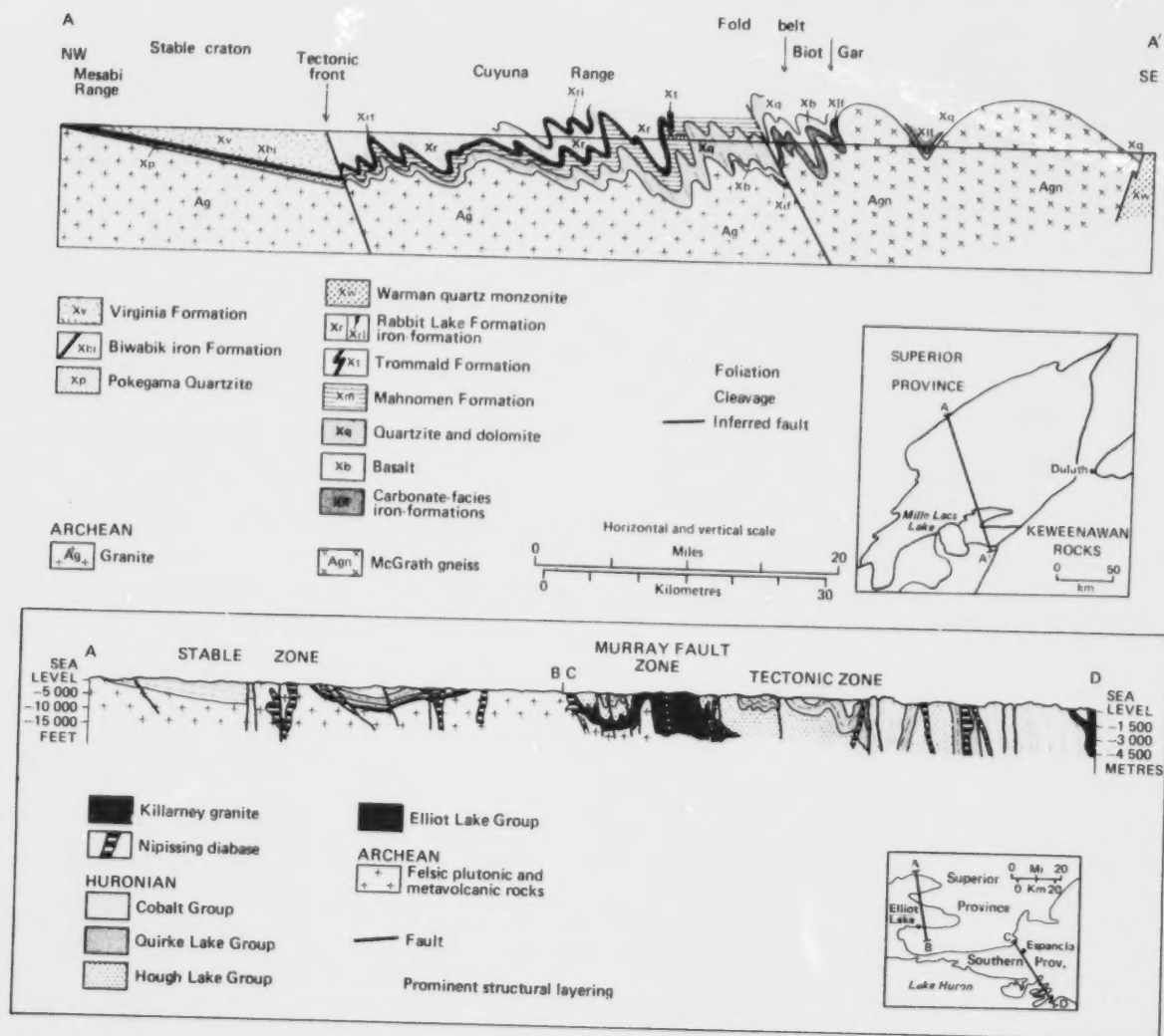


Figure 2.4. Cross section showing the structure across the Southern Province in Ontario and Minnesota (after Sims *et al.* 1981).

volcanic rocks that extend southward into the mid-continent region. Zolnai (1982) concluded that tectonic relief across the MFZ is 10 to 15 km. Consequently, the GLTZ-MFZ system has major dimensions and a long, complex history. The Sudbury Structure is located on the northern margin of the Murray Fault Zone, and may represent one more manifestation of Proterozoic activity along this long-lived crustal structure.

TECTONIC SETTING

Various tectonic models have been proposed for the Early Proterozoic rocks of the Southern Province, but in general these can be described in terms of an intracratonic, ensialic setting versus a continental margin setting. Card and Hutchinson (1972) and Card (1978a) considered the Huronian depositional basin as an elongate, graben-style trough bounded on both sides by Archean rocks. Sims *et al.* (1980, 1981) proposed that the Early Proterozoic sequences were deposited in fault-controlled, ensialic basins developed along a major east-trending structure, the Great Lakes Tectonic Zone. Young (1982) proposed that the Early Proterozoic rocks were deposited in an aulacogen that opened eastward into what is presently the Grenville Province.

Van Schmus (1976), Cambray (1978), and Larue and Sloss (1980), among others, have proposed a continental margin setting for the Early Proterozoic rocks of the Lake Superior region. Van Schmus postulated a south-facing miocline developed along a consuming continental margin that was subsequently deformed and intruded as a result of northward-dipping subduction. Cambray and Larue and Sloss invoked a similar scheme, but with south-dipping subduction and orogeny due to a terminal continent-continent collision. Zolnai (1982) has recently proposed that the Huronian Supergroup is a passive margin sequence deposited during rifting and ocean basin formation along the southern margin of the Superior Province craton. This margin sequence collided at 1850 ± 50 Ma with a southern, unidentified granitoid terrain, and this resulted in northward thrusting and shortening of the Huronian supracrustal wedge by more than 30% against the Superior Province craton.

Available data are not adequate to conclusively choose among the various models proposed, but no matter which model is favoured, Sudbury is in an unusual setting located either along an Early Proterozoic rift, a rifted Archean craton margin north of a subduction zone, or near the junction of an aulacogen and a continental margin. The emplacement of the Sudbury Igneous Complex, as indicated by the U-Pb zircon age of the norite of 1849 ± 3 Ma, is penecontemporaneous with the late stages of the Penokean Orogeny, an event that affected the entire Southern Province.

Grenville Province

The Grenville Province east of Sudbury is a gneissic terrain that has a complex history of tectonism culminating in major orogenesis about 1200 to 1000 Ma (Lumbers 1975). The northwestern part of the Grenville Province, the Grenville Front Tectonic Zone (GFTZ, Figure 2.2), is a northeast-trending zone approximately 30 km wide, characterized by northeast-trending cataclastic foliation and southeast-plunging rodding lineation that transects older structural trends in the adjacent Superior, Southern, and Grenville Provinces (Figure 2.2). Evidence exists for both northwest-directed thrusting and dextral shear along the GFTZ (Lumbers 1975).

Archean rocks, including felsic plutons and possibly metasedimentary gneiss equivalent to the Pontiac Group of the Superior Province (Davidson *et al.* 1979), are recognized in the northwestern part of the Grenville Province. So too are plutonic rocks and metasedimentary gneiss of Proterozoic age, some of which are equivalent to rocks of the Southern Province, notably the Huronian Supergroup. However, it is not certain how much gneissic rock of the northwest Grenville Province is equivalent to Archean or Proterozoic rocks of the adjacent terrain, nor how far into the Grenville Province these units extend. Davidson *et al.* (1982) have recently proposed a Himalayan-type collisional tectonic model for the Grenville with allochthonous crustal segments being transported northwestward by ductile shear and thrusting, probably at deep crustal levels. According to this model, any Huronian or Archean rocks that did exist here may well have disappeared under a stack of allochthonous thrust slices.

EFFECTS OF GRENVILLE PROVINCE OROGENIC EVENTS ON THE SUDBURY STRUCTURE

The Sudbury Structure is located some 10 km northwest of the Grenville Front, the faulted northwest margin of the Grenville Province. Orogenic events centred in the Grenville Province may have affected the Sudbury Structure and adjacent parts of the eastern Southern and Superior Provinces. In fact, Brocoum and Dalziel (1974) have proposed that deformation of the Sudbury Structure, the eastern Southern Province, and the adjacent Grenville Province occurred during a protracted orogenic event some 1600 to 1900 Ma ago.

The effects of any Early Proterozoic events centred in the Grenville cannot be distinguished from those of previously described events that affected most of the Southern Province. It is possible that the same Early Proterozoic events did affect both the Grenville

and Southern Provinces. It is equally possible, however, that the Grenville Province was not even part of the North American craton in the Early Proterozoic.

The intense Middle Proterozoic events in the Grenville Province have not greatly affected the Southern Province, including the Sudbury Structure. The Grenville Front is essentially the northern limit of penetrative Grenvillian deformation and high-grade metamorphism. Rock units younger than the 1750 to 1900 Ma events of the Southern Province and older than the 1000 to 2000 Ma events of the Grenville Province, for example, the Chief Lake (1700 Ma) and Killarney (1500 Ma) granites, and the olivine diabase dikes (1250 Ma), are not deformed or metamorphosed north of the Front. Late movements occurred on some faults, including some that cut the Sudbury Structure. Uplift probably occurred at this time as shown by the regional disturbance of the K-Ar isotopic systems (Van Schmus 1965). The major deformation of the Sudbury Structure, notably of its southern part, must have occurred prior to 1250 Ma and probably prior to 1700 Ma ago.

REGIONAL GEOPHYSICAL CHARACTERISTICS

Variations in the earth's magnetic and gravity fields commonly correspond to lithologic, metamorphic, and structural features over a range of depths within the crust. Analysis of the magnetic and gravity fields provides a means of making inferences regarding both the surface and internal characteristics of the crust. The analysis is complicated because of the inherent ambiguity of potential field interpretations. Pattern changes on gravity and magnetic maps related to short wavelength anomalies, however, can be related to small-scale, near-surface geologic effects, whereas pattern changes containing both short and long wavelength components are usually caused by large-scale, near-surface sources. Pattern changes possessing only long wavelength components are normally attributable to deeper crustal features. Because geophysical observations are generally made close to earth's surface, shallow source information tends to dominate geophysical maps and to mask long wavelength, deeper source anomalies.

Further, unlike gravity anomalies to which the contribution of deep sources is limited by detectability, magnetic anomaly sources are restricted to an outer layer of crust that extends only to the Curie isotherm, the depth at which ferromagnetic behaviour ceases. Crustal temperature profiles, based on surface heat flow and conductivity and radioactive heat generation estimates (Jessop and Lewis 1978), suggest that the Curie isotherm is well within the upper mantle in the Sudbury region.

To accompany the following discussion, a coloured magnetic map (Map NL-16/17-AM, back pocket) and a Bouguer gravity map (Chart A, back pocket) of the region are included. The 1 000 000 scale magnetic map was produced using digital data derived from 1:50 000 scale Federal-Provincial aeromagnetic maps (Dods *et al.* In Press). The standard survey parameters used for raw data collection were a flight line spacing of 805 m with a mean terrain clearance of 305 m. The digitizing interval for the magnetic map was 812.8 m. During compilation of the map, appropriate International Geomagnetic Reference Field model data representing the core-generated magnetic field (IAGA Division I Working Group 1981) were subtracted to give data commonly referred to as the crustal, residual, or anomalous component of the geomagnetic field. Also included is a photograph of a shaded-relief magnetic map (Figure 2.5a) prepared from the same data set used to generate the coloured magnetic map. Like topographic data, magnetic anomaly data can be artificially illuminated from any given azimuth and inclination angle (Horn and Bachman 1978).

The Bouguer gravity map of the region was prepared using gravity data of the Earth Physics Branch of the Department of Energy, Mines and Resources for that part north of Latitude 48°N and of the Ontario Geological Survey for that part south of this latitude. Average gravity station spacing in the north was approximately 13 km and in the south, 2.5 km. The data for the entire region have been gridded at 5 km intervals in both north-south and east-west directions; this cell size is the most convenient compromise between undersampling of the data in the north and oversampling in the south. A generally good correlation between geology and the gravity field exists, and to bring this correlation into sharper focus, an apparent density map (Figure 2.6) has been prepared from the gravity data. The basis of apparent density mapping consists of dividing the terrain into vertical-sided prisms of fixed depth extent on a grid having the same dimensions as the data set. The mean densities of the prisms are calculated such that their aggregate gravity effect matches the gridded Bouguer gravity values. In the interpretive map (Figure 2.6), the boundaries of lithodensity units were determined from gravity gradients and the lithologies of the lithodensity unit from apparent density values.

Superior Province

The Archean Superior Province north of Sudbury has generally higher magnetic background values than do the Southern and Grenville Provinces to the south. There are a number of high-amplitude long-wavelength anomalies over the Superior crust that are attributable to either, large shallow magnetic sources, or,



Figure 2.5a. Shaded-relief magnetic map of the Sudbury region: A - Preissac dikes; D - fault; E - fault?; G - Gowganda Formation; GF - Grenville Front; IF - Iron Formation; K - Kapuskasing Zone; KL - Killarney Batholith; M - Matachewan dikes; MI - Manitoulin Island intrusions; PS - Parry Sound anomalies; S - Sudbury anomaly; SD - Sudbury dikes; T - Temagami anomaly. Location of magnetic profiles: F-G and H-I, Temagami anomaly, Figure 2.8; X-X', regional magnetic profile, Figure 2.9.

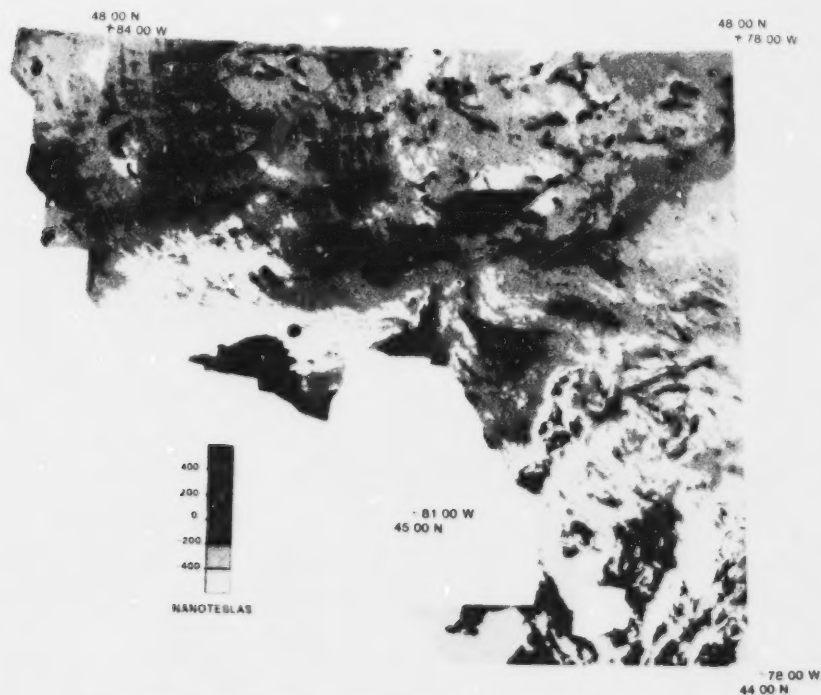


Figure 2.5b. Upward continued total field magnetic map of the Sudbury area.

to smaller, but deeper magnetic sources within the crust.

Archean "greenstone" belts are marked by aeromagnetic lows with local linear positive anomalies over iron formations (IF, Figure 2.5a). Archean gneissic units produce little magnetic signature, as do granodioritic and tonalitic intrusions. In contrast, high-grade gneiss of the Kapuskasing Zone (K, Figure 2.5a), and late potassic granites, syenites, and gabbro-syenite complexes produce positive magnetic anomalies. The large Algonian batholiths north and west of Sudbury are particularly magnetic, possibly due to the presence of finely disseminated magnetite in fractures in the otherwise fresh granite. The Algonian granites also give rise to uranium, thorium, and potassium anomalies on airborne radiometric survey maps (Char-

bonneau 1982). Numerous linear and curvilinear magnetic anomalies throughout the region mark diabase dikes of several swarms including north-trending Matachewan dikes (M, Figure 2.5a), northeast-trending gabbro dikes (A, Figure 2.5a), and northwest-trending Sudbury dikes (SD, Figure 2.5a). Discontinuities in the magnetic patterns, for example along the southeastern boundary of the Kapuskasing anomaly (D, Figure 2.5a), are probably attributable to faults. An east-northeast-trending discontinuity north and west of Sudbury (E, Figure 2.5a) may also mark the trace of a fault zone.

There is good correlation between the gravity field and major lithotectonic units of the Superior Province. The Abitibi-Swayze volcanic domain is expressed as a distinct positive feature on the gravity map (See

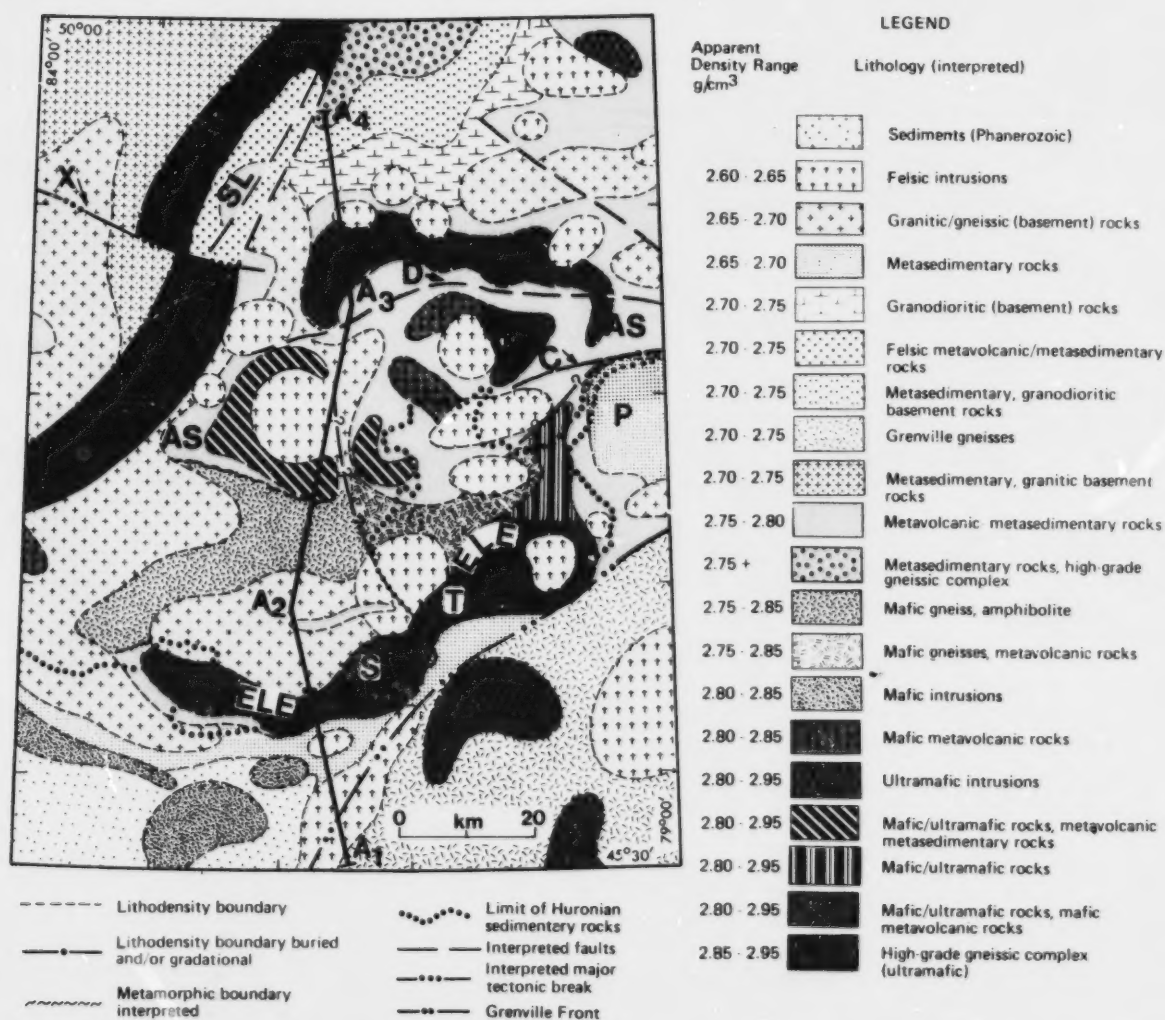


Figure 2.6. Lithodensity map of the Sudbury region: AS - Abitibi-Swayze volcanic domain; C - Kirkland Lake-Cadillac Fault; D - Destor-Porcupine Fault; ELE - Elliot Lake-Englehart gravity anomaly; K - Kapuskasing structure; P - Pontiac Belt; S - Sudbury anomaly; SL - Saganash Lake Volcanic Belt; T - Temagami gravity anomalies; X - possible fault. A₁-A₂-A₃-A₄ - location of regional gravity profile, Figure 2.7.

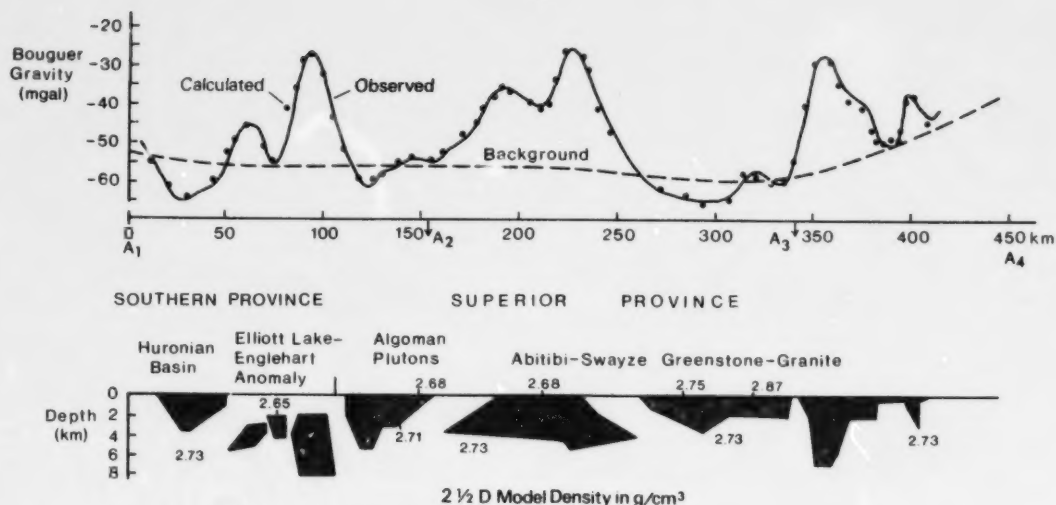


Figure 2.7. Regional gravity profile for the Sudbury region. Location given on Figure 2.6 Dots - Proterozoic sedimentary rocks; Crosses - Archean granite; Diagonal lines - Archean "greenstone"; Cross-hatch - mafic-ultramafic bodies; Blank - Archean gneiss and unknown.

Chart A; AS, Figure 2.6). The gravity values suggest a concentration of mafic-ultramafic rocks around the rim of this domain and a generally less mafic interior. The southern boundary of the domain extends beneath the Cobalt Embayment, while the northern boundary is precisely indicated by the gravity map. The southern part of the Abitibi Belt and the Temagami "greenstone" belt can be traced beneath the Huronian rocks of the Cobalt Embayment which are generally about 4 to 7 km thick. The Pontiac Metasedimentary Belt (P, Figure 2.6) south of the Abitibi "greenstone" belt has an apparent density of 2.65 to 2.70 g/cm³, indicating a high proportion of light sedimentary and granitic rocks. The orthogneiss units have variable apparent densities (2.6 to 2.85 g/cm³) attributable to their heterogeneous characteristics; notably, variation in the relative proportions of tonalite-granodiorite gneiss, mafic and amphibolite enclaves, and granitic intrusive material. Granite plutons are outlined by gravity lows; many have apparent densities between 2.6 and 2.7 g/cm³ indicating that they are relatively uncontaminated. Major fault zones such as the Destor-Porcupine (D, Figure 2.6) and Kirkland Lake-Cadillac (C, Figure 2.6) structures are indicated by weak, linear gravity lows. The fact that these narrow features can be perceived in such coarsely gridded data suggests that they are of major dimensions. A profile (Figure 2.7) across part of the region shows that the gravity field can be modeled using a background density of 2.73 g/cm³ for the upper 10 km of the crust. Within this matrix, which would correspond approximately to tonalite-granodiorite gneiss, there are denser bodies (2.75-2.9 g/cm³) corresponding to "greenstone" belts and mafic intrusions, and lighter bodies (2.6 to 2.7 g/cm³) corresponding to felsic plutons and sedimentary rocks. The Archean "green-

stone" belts generally extend to depths of < 5 km; locally, there are "roots" extending to 7 km. Similarly, the granitic plutons are probably tabular, extending to depths of 3 to 5 km.

The most striking feature of the region is the Kapuskasing gravity high, remarkable for its magnitude (approximately +50 mgal) and linear continuity (K, Figure 2.6). The anomaly indicates a mass of dense rock (average density approximately 2.95 g/cm³) having a moderate to gentle westward dip. A sharp flexure in the gravity contours at about Latitude 49°N suggests left lateral displacement of approximately 30 km along an east-southeast trending discontinuity (X, Figure 2.6). This proposed discontinuity is approximately in line with the Destor-Porcupine Fault to the east and with the Quetico-Wawa Subprovince boundary to the west, and may represent a major fault. However, the interpretation that the Kapuskasing Zone has been offset by an east-southeast-trending fault must be treated with caution since the density of gravity stations in the area is low. Kapuskasing-type paragneiss and mafic granulite gneiss are exposed east of the Saganash Lake Volcanic Belt (SL, Figure 2.6), and no granulite gneisses are known west of the Saganash Lake Belt. The Kapuskasing structure probably consists of a number of fault blocks in this region, some with granulites exposed at surface, others with dense rocks in the shallow subsurface.

Southern Province

Southern Province features are not well-defined by the gravity field. There are weak gravity lows over the thicker parts of the Huronian sequence in the area

along the northern shore of Lake Huron. There are positive anomalies over a gabbro-anorthosite intrusion and Huronian volcanic rocks, and 2 small positive gravity anomalies (T, Figure 2.6) in the Lake Temagami area may correspond to the magnetic anomaly-causing bodies in this area. A negative anomaly over Lake Wanapitei may mark an impact crater (Dence and Popelar 1972).

The dominant feature of the gravity field is a linear positive anomaly that extends some 350 km from Elliot Lake eastward through Sudbury (S, Figure 2.6) and northeastward to the Englehart area. This feature, interpreted as a mafic-ultramafic body at depth, is herein termed the Elliot Lake-Englehart Gravity High (ELE, Figure 2.6). The most intense positive gravity anomalies of the ELE are located near Elliot Lake, Sudbury (S), Lake Temagami (T), and Englehart. In the Superior Province north and west of Sudbury, an east-northeast-trending body of anomalously high apparent density crosses the granitic-gneissic Archean terrain, linking the ELE gravity high with the south-western end of the Swayze "Greenstone" Belt. The apparent density values of this body ($2.75\text{--}2.85\text{ g/cm}^3$) indicate that it is mafic gneiss or amphibolite. The mafic gneiss unit and the ELE mafic-ultramafic body would thus appear to form a relatively continuous, dense crustal unit extending southward from the Swayze Volcanic Belt to Elliot Lake and eastward through Sudbury to the Abitibi Belt near Englehart. Much of this mafic-ultramafic zone is not exposed, although it coincides in part with mafic gneiss in the Ramsay Gneiss Domain (RGN, Figure 2.2), zones rich in mafic enclaves between major Algoman batholiths, Archean mafic volcanic rocks near Elliot Lake and Lake Temagami, and gneiss of the Levack Gneiss Complex near Sudbury.

In the Southern Province, the Huronian sedimentary and volcanic rocks and the Nipissing intrusions are

mainly weakly magnetic. One stratigraphic unit in the Gowganda Formation does produce a low positive anomaly that outlines fold structures (G, Figure 2.5a). As a consequence of their generally low intensity of magnetization, the Huronian rocks have a "blanketing" effect which tends to produce lower background values over areas covered by such rocks relative to areas of exposed Archean basement. In the Sault Ste. Marie-Elliot Lake and Cobalt Embayment areas, where the Huronian cover is relatively thin ($< 5\text{ km}$), anomalies produced by magnetic Archean rock units such as iron formations and mafic dikes are discernible through the cover. The most striking of these is an anomaly immediately east of the Sudbury structure near Lake Temagami which is similar in shape and size to the Sudbury magnetic anomaly, but which has a far greater amplitude. The Temagami anomaly (T, Figure 2.5a) is composite, made up of a small wavelength component caused by Archean iron formation which outcrops within an area of Archean basement near its eastern end, and a long wavelength component produced by an anomaly-causing body which appears to be mainly intrabasement. To the west, the causative body may be covered by as much as 5 km of Proterozoic rocks. Combined, these 2 sources produce an anomaly as large as 10 000 nT, which is one of the largest aeromagnetic anomalies over the Canadian Shield. Coles *et al.* (1981) suggested that the causative body extends as deep as 15 km into the crust.

Figure 2.8 illustrates 2 profiles over the Temagami anomaly. The observed data, represented by the dashed lines, were digitized at a 370 m interval on one inch to one mile aeromagnetic maps (GSC Maps 1502G, 1503G). A background value of 2000 nT, and a regional trend were removed from the digitized data. The regional trend was calculated using International Geomagnetic Reference Field model data backdated to 1960, the year the survey was flown. The mean terrain

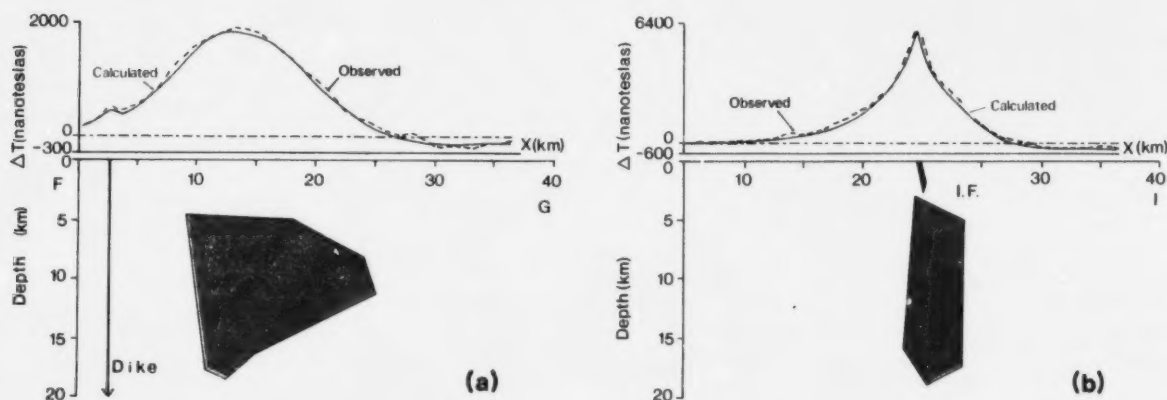


Figure 2.8. Magnetic profiles and interpretation of the Temagami anomaly. See Figure 2.5a for location.

clearance of the airborne survey was 305 m and the magnetometer was a fluxgate type. To model the resultant digitized data, it was assumed that the causative bodies could be approximated by $2\frac{1}{2}$ dimensional, n -sided, right-polygonal models. Initial magnetic profiles for the assumed models were calculated and compared to the observed data. To bring the calculated and observed profile data into closer agreement, an interactive computer procedure (McGrath *et al.* 1983) was utilized. Parameter values of the earth's main magnetic field used in the interpretation were 59275 nT for intensity ($1 \text{ nT} = 1 \text{ gamma}$), 76°N for inclination, and 8°W for declination (Earth Physics Branch F, I, and D magnetic charts of Canada, 1965). The polarization direction of the causative bodies was assumed to be coincident with the direction of the earth's ambient field. Best-fit model anomaly curves are illustrated in Figure 2.8 by solid lines.

The observed data shown in Figure 2.8a can be reproduced by 2 anomalous bodies. The main body is funnel-shaped in cross section, and has a strike length of 10 km, which was estimated from the aeromagnetic maps. The upper surface of the body is at a depth of 5 km, its maximum width is 15 km, and it extends to a depth of 15 to 20 km. The structure appears to be tilted to the north, and some evidence suggests a feeder exists under the southern side of the body. The interpreted effective susceptibility contrast, K , for the body is 0.238 SI ($1 \text{ SI} = 4\pi \text{ cgs units}$). If the magnetization of the enclosing rocks is assumed to be negligible and the magnetization of the causative bodies is dominated by induction, a volume percent, V , of 6% magnetite is required to produce a susceptibility of this value, where V is calculated from the equation, $V = 21.8 K^{0.90}$, derived from an empirical susceptibility formula by Balsley and Buddington (1958). This is a rather large susceptibility value, but still within the range of many rock types. According to a table of susceptibility values published by Dobrin (1976), the causative body could be of syenitic, dioritic, basic, or ultrabasic composition. The second body modelled in Figure 3.8a represents a Sudbury dike which is known to cross the southern end of the profile in a northwesterly direction. For the purposes of interpretation, the strike length and the depth extent of the dikes were assumed to be infinite. The interpreted effective susceptibility contrast for the dike is 0.129 SI based on an assumed thickness of 0.1 km. The susceptibility contrast would be equivalent to an average magnetite content of 3.4%.

The observed data illustrated in Figure 2.8b are quite different from that discussed for Figure 2.8a. In this case, the anomaly amplitude is much greater, and it is evident that the anomaly is attributable to 2 closely spaced sources. Interpretation suggests that the Archean iron formation extends from the surface to a

depth of 2.5 km, and dips steeply to the north. The susceptibility contrast obtained was 0.821 SI based on an assumed thickness of 0.1 km. This is equivalent to a magnetite content of 18.0% by volume for the iron formation. The lower body has a more tabular shape than does the related body to the west. It extends from a depth of 3.0 to 18.0 km, and has a width of 5 km. The effective susceptibility contrast required in this case was 0.736 SI for an equivalent magnetite content of 16.5%. This is an exceptionally large value, larger than reported by Dobrin (1976) for typical rocks, and Cornwell (1975) for normal Precambrian rocks in northern Sweden. One possible rock type for the causative body is iron formation. However, it is unlikely that such a large body would be of this rock type. The most probable source would appear to be a serpentinized basic or ultrabasic body. Although these suggestions must be regarded as speculative, it is evident that a large, strongly magnetic, intrabasement body exists east of Sudbury. This body is more magnetic at its eastern than at its western end, and appears to shallow slightly toward the east. The close spatial association and similarity of the Temagami and Sudbury anomalies suggests the possibility of a genetic relationship between the two. Furthermore, the occurrence of magnetite and hematite in fractures and seams in the Algoman granite west of Sudbury may be a reflection of serpentinization of a mafic or ultramafic layer at depth. These possible interrelationships are enhanced by the association of the 3 magnetic sources with the Elliot Lake-Englehart gravity anomaly.

Southwest of Sudbury along the North Channel of Lake Huron, an intense east-west magnetic low (see coloured magnetic map, Map NL-17AM, back pocket) exists over the thickest part of the Huronian section. This low, the North Channel Magnetic Anomaly, may be due to a very thick accumulation of Proterozoic rocks, to a change in character of the basement, to intense magnetic highs over 1500 Ma old Manitoulin Island intrusions which occur to the south of the low, or to all three. In order to analyze this magnetic feature, a profile traversing the anomaly was digitized at a 370 m interval on 1 inch to 1 mile aeromagnetic maps (GSC Maps 2239-43G, 2269G, and 3237G). The profile extends along Longitude 83°W from Latitudes $45^\circ 45' \text{N}$ to $47^\circ 15' \text{N}$. The profile traverses 3 airborne survey areas which were flown in different years in the period from 1954 to 1963. The mean terrain clearance for the surveys was 305 m, except for the data on Map 3237G (GSC) which was flown at a mean terrain clearance of 152.5 m. The 3 surveys were conducted using either fluxgate (relative) or proton precession (absolute) magnetometers. To prepare the digitized data for interpretation, the profile segment crossing Map 3237G (GSC) was continued upward to 305.0 m; International Geomagnetic

Reference Field model data, backdated to the year a given survey was flown, were calculated and subtracted from the appropriate profile segments. The segments over areas flown with fluxgate magnetometers were tied to those segments flown with proton precession magnetometers using common points at the survey margins. The resultant composite profile consisted of a large data set, and because of limited storage available within the interactive interpretation software (McGrath *et al.* 1983), it was necessary to upward continue the profile data from the flight elevation of 305 m to 1220 m and then to decimate the resultant data to a 1.85 km sampling interval. This procedure reduced the number of observed data points, prevented aliasing problems (Kanasewich 1973), and simplified the interpretation by reducing the contribution of local magnetic sources to the profile data. To interpret the observed data (Figure 2.9), it is assumed that a major part of the profile is underlain by Archean tonalite-granodiorite gneiss with numerous "greenstone" enclaves, and massive to foliated granite, granodiorite, and syenite intrusions. Toward the centre of the profile, the gneisses are overlain by Huronian metasedimentary and volcanic rocks, whereas to the north, the gneisses are intruded in part by the Algonian granite. At the southern end of the profile, a body representing a Manitoulin Island intrusion overlain by Paleozoic cover is also modelled. The strike lengths of the models representing the Huronian rocks and the Algoma gneiss and plutonic domains were assumed to be very large, while that of the Manitoulin Island intrusion was estimated to be 30 km. Further, it was assumed that all bodies were magnetized in the direction of the ambient geomagnetic field. The resultant interpretation is illustrated by the solid line shown in Figure 2.9. The interpretation suggests that the contact between the gneiss and Algonian granite pluton dips to the north at an angle of 15° to 20°. Effective susceptibilities of 0.0064 and 0.021 SI were obtained for the gneiss and the plutonic rocks respectively, assuming zero magnetization for the Huronian rocks. It was not

possible, however, to model the North Channel magnetic anomaly using a realistic estimate of the depth extent of Huronian cover rocks, or with reasonable values for intensities of magnetization of the basement and the Manitoulin intrusion. The negative anomaly over the Huronian section is far more intense than can be obtained using existing geological models of the region.

The main area of departure of the model from the observed curve extends from the Manitoulin Island intrusion in the south to the Murray Fault Zone in the north. This departure suggests a major change in the basement under this area. The Huronian rocks may rest on non-magnetic oceanic crust rather than resting on Archean basement as exists farther to the north. This is unlikely because there is no large gravity anomaly associated with the negative magnetic anomaly, as would be expected over a basaltic basement juxtaposed against a less dense granitoid basement. However, if it is assumed that the basement in this area is indeed Archean, it must have been considerably altered from that typically seen to the north. It is possible that Archean crust under the North Channel area has been oxidized by fluids or the basement under the Huronian section may possess a strong remanent magnetization which opposes the present direction of the geomagnetic field. It would be easy to produce the required negative anomaly in this manner, but again it seems unlikely. Large negative anomalies are found along many geologic province boundaries, for example along the Thelon Front at the eastern edge of the Slave Province. It is doubtful that all of these anomalies can be explained by reversed magnetization, especially in view of the fact that these boundary zones are of many different ages. Some indication as to the cause of the North Channel magnetic anomaly may be inferred from the Slave area. J.B. Henderson (Geologist, Geological Survey of Canada, Ottawa, personal communication, 1983) noted the coincidence of a component of the Thelon magnetic low with a zone of intense shearing. Hence, it is possible to infer that the North Channel magnetic anomaly may result from pervasive shearing of the basement rocks along major zones of faulting and cataclasis with possible additional modification by circulating fluids.

Grenville Province

The Grenville Province has generally low magnetic background values and short wavelength anomalies that are apparently mainly attributable to shallow magnetic sources. The Grenville Front is expressed by a discontinuity in the magnetic pattern which is locally enhanced by a zone of moderately intense circular anomalies (Map NL-17AM; GF, Figure 2.5a). South of the Grenville Front and east of Sudbury, there is an area of high magnetic intensity that apparently continues

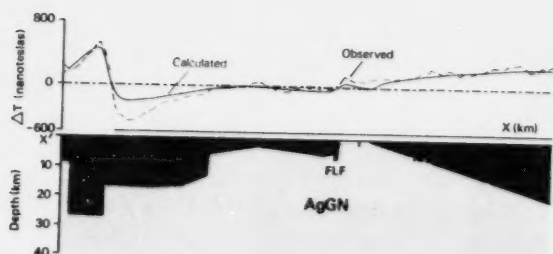


Figure 2.9. Magnetic profile and interpretation of the North Channel-North Shore of Lake Huron region. Pa - Paleozoic cover; MI - Manitoulin Island intrusions; P - Proterozoic strata; MF - Murray Fault; FLF - Flack Lake Fault; AgGN - Archean gneiss; AgPD - Archean Algonian plutons.

eastward and northward into the Pontiac Belt of the Superior Province. It is possible that the rocks south of the Grenville Front in this area are the modified equivalents of the Pontiac paragneiss and granitoid rock of the Superior Province. Southeast and south of Sudbury, there is an area of lower magnetic intensity over gneisses that may represent modified Archean and Proterozoic rocks, some of which may be equivalent to the Huronian Supergroup of the Southern Province. A number of positive anomalies in the area are situated over plutonic bodies, the most prominent of which are associated with the 1500 Ma old Killarney Batholith (KL, Figure 2.5a). This zone of modified, possibly Archean and Early Proterozoic crust southeast of the Grenville Front is approximately 60 to 80 km wide. Farther to the southeast, there is an area of lower magnetic intensity with complex, cell-like magnetic patterns and sinuous positive anomalies (PS, Figure 2.5a). In the Parry Sound area, these magnetic patterns correspond closely to structural domains outlined by Davidson *et al.* (1982).

The Grenville Front is not expressed in the gravity field, as several regional anomalies appear to cross this structure without interruption. This lack of gravity expression would support the interpretation that the northwestern part of the Grenville Province in this region represents modified Archean and Proterozoic rocks corresponding to Superior and Southern Province sequences. In the north, a positive gravity anomaly corresponds to the River Valley anorthosite (Lumbers 1975). In the south, there are a number of gravity domains that correspond in part to structural domains outlined in the Parry Sound area (Davidson *et al.* 1982; Lindia *et al.* 1983).

SUMMARY AND CONCLUSIONS

The foregoing analysis has, in our opinion, demonstrated that the Sudbury Structure is clearly associated with particular rock units, structures, and events some of which are of regional extent. The Sudbury Structure is associated with the Archean Levack Gneiss Complex of the Superior Province. The Levack gneisses have characteristics indicating that at one stage in their history they were at middle or lower crustal depths. Uplift of these rocks apparently occurred before or during emplacement of the Algonian granites some hundreds of million of years before the Sudbury Event. The Sudbury Structure is spatially associated with particular Early Proterozoic supracrustal sequences of the Southern Province, the only thick accumulations of submarine volcanic rocks and turbidites in the eastern part of the Southern Province. The Sudbury Structure also is spatially associated with a structure of continental and crustal dimensions, the Great Lakes Tectonic Zone. This zone controlled the development and evolution of the Southern Province basins throughout

the Great Lakes region and may represent the margin of an intracratonic rift or a suture zone between converging crustal plates.

Development of the Sudbury Structure, including the formation of a large crater, brecciation and shattering of the country rocks, deposition of the White-water Group, and emplacement of the Sudbury Igneous Complex and a possibly cogenetic hidden mafic-ultramafic complex (Gupta *et al.*, Chapter 18, this volume), apparently occurred over a restricted period of time about 1850 Ma ago. Consequently, the Sudbury Event is closely associated in time, as well as in space, with Proterozoic orogenesis that affected the entire Southern Province.

All of the foregoing inter-relationships have been previously enunciated (Card and Hutchinson 1972). In this paper, a number of new concepts and hypotheses relating to Sudbury have been introduced as a result of the geophysical studies. The Sudbury Structure occurs within a linear zone of dense rocks that extends from Elliot Lake through Sudbury and Lake Temagami to Englehart in the southern part of Superior Province and the northern part of the Southern Province. The Sudbury anomaly is only one of several gravity-magnetic anomalies that occur along the ELE gravity high. The ELE anomaly may represent a relatively homogeneous body of rock analogous to mafic-ultramafic complexes such as the Great Dyke or the Muskox Complex. It may also represent a variety of rock units of diverse ages and origin which are all anomalously dense and magnetic.

In conclusion, the regional geological-geophysical setting of the Sudbury Structure and its association with particular rocks, structures, and orogenic events all indicate that it may be only one of several features formed over a long period of time in a particularly active part of the earth's crust.

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CHAPTER 3

The Regional Metallogenetic Setting of Sudbury

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ABSTRACT

The area of approximately 100 000 km² encompassing Sudbury has experienced a complex geological history throughout the Precambrian. Several of the geological events recorded in the rocks of the area have caused concentration of metallic minerals. Numerous significant ore deposits of a variety of ages and types are present in addition to the major deposits associated with the Sudbury Igneous Complex. The volcanogenic base-metal sulphides of the Kidd Creek type, the paleoplacer uranium deposits of the Elliot Lake area, and the silver vein deposits of the Cobalt area are most prominent examples.

The metallogenetic development of this area is an integral part of its overall geological development; the sequence of metallogenetic processes can be largely explained in that context. The proposed metallogenetic model demonstrates systematic processes of

metal introduction and concentration in the crust during magmatism and redistribution of metals by subsequent magmatic, sedimentary, and metamorphic processes which were the result of tectonism. This model shows that the formation of the major ore deposits of the Sudbury Igneous Complex can be viewed as one of many metallogenetic events to have affected this area.

The Sudbury area is a Ni, Cu, PGE metallogenetic province that has been associated with 2 distinct magmatic events over a period of 600 million years before the formation of the Sudbury Igneous Complex. In addition, this period of the earth's development is characterized by major magmatic mineral deposits associated with large mafic intrusions. The metallogenetic style of the ore deposits of the Sudbury Igneous Complex are, therefore, consistent with their location in time and space.

INTRODUCTION

The main purpose of this chapter is to describe the characteristic mineral deposits of the region encompassing Sudbury. A diverse range of types and styles is present. Specific examples of each are listed. In addition, the economic importance of many of the deposit types represented in this region is demonstrated. Economic considerations are, however, only one aspect of the importance of mineralization.

The geological processes which resulted in concentration of mineralization are an integral part of the overall geological development of this region. In the later part of the chapter, therefore, the patterns of metal distribution are considered in the context of original introduction of metals into the crust and subsequent stages of dispersion and concentration by erosional, sedimentary, magmatic, and metamorphic processes. The metallogenetic model which is presented shows a well-defined metallogenetic province, encompassing Sudbury, and that this is consistent with a metallogenetic epoch over the 1 billion year period of the Late Archean and Early Proterozoic. This model permits the examination of the metallogenetic development of the Sudbury Igneous Complex in the context of its overall metallogenetic setting. The implications which can be drawn from this are briefly discussed.

CHARACTERISTIC MINERAL DEPOSITS

The area of diverse geology covered by this discussion, shown in Figure 3.1, and described by Card *et al.* (Chapter 2, this volume), contains many present and past producing mines. In addition, more than 2000 known anomalous mineral concentrations of a wide variety of styles and types exist. The principal deposit types encountered are briefly described and specific examples are given, where possible. The overall distribution of mineralization and discussion of its significance are addressed in subsequent sections.

Archean Mineralization

The Archean was an epoch of major introduction of metals and their selective concentration in the earth's crust. In the Sudbury region, copper, zinc, silver, gold, iron, and nickel, and a range of associated metals, have all been economically extracted. Metal distribution was strongly influenced by the major lithological subdivisions in this area of complexly interrelated granitoid, gneissic, and volcano-sedimentary ("greenstone") sequences.

"Greenstone" belts host the majority of mineral deposits in the Shield. Polymetallic base- and precious metal massive sulphide deposits were produced by

volcanic exhalative activity in the upper felsic part of many volcanic sequences; the Kidd Creek Mine, north of Timmins, is one of the largest of these in the world. Closer to Sudbury, the Geneva Lake and Stralak Deposits in the Benny Greenstone Belt (Figure 3.1, #1) are relatively small examples.

The "greenstone" belts also contain major lode gold deposits commonly hosted by quartz vein systems. Unlike the massive sulphides, these do not have a consistent lithologic or stratigraphic setting; they normally occur with mafic volcanic rocks, commonly adjacent to clastic sedimentary sequences and frequently are also associated with felsic intrusions. The association of gold with zones of apparent structural discontinuity or "breaks" has long been recognized, particularly in the Timmins and Kirkland Lake areas of the Abitibi Belt (Dunbar 1948; Thomson 1948), which host the largest known Shield concentrations of lode gold mineralization. The volcanic-hosted Tyrenite Mine (Figure 3.1, #2) and the syenite-hosted Matatchewan Consolidated Mine (Figure 3.1, #3) are specific examples.

Algoma-type banded chert-magnetite iron formation is also present in most "greenstone" belts, hosted by mafic volcanic rocks or clastic sediments (for example, Sherman Mine, Figure 3.1, #4). Locally, these may host recoverable gold values (for example, Emerald Lake Mine, Figure 3.1, #5) and anomalous base-metal concentrations (for example, Moose Mountain Mine, Figure 3.1, #6) (Lortie 1983).

Komatiitic units in the lower part of many "greenstone" sequences can host recoverable nickel mineralization (Coad 1979), for example, the Langmuir Mine in the Timmins area. These units are also relatively enriched in chromium and titanium. Altered komatiites have also been exploited for asbestos (Figure 3.1, #7) and talc (Kretschmar and Kretschmar 1982). Gabbroic intrusions may also host magmatic-style mineralization (for example, the Kanichi Mine (Figure 3.1, #8) which produced Ni-Cu and PGE).

The large areas of the Shield which surround the obvious volcanic-sedimentary complexes, which consist of granitic and gneissic rocks, have been subdivided by Card (1979) into domains of orthogneisses, paragneisses, and plutonic suites. The paragneiss suites, which represent highly metamorphosed "greenstone" sequences, have the potential for much of the mineralization characteristic of "greenstone" belts.

Granitoid and orthogneiss suites also host characteristic metal concentrations, principally copper, molybdenum, and uranium, but few important examples have been identified; the Krystina Copper Deposit (Figure 3.1, #9) may be an example. The Algoma Pluton, to the north of Elliot Lake and Agnew Lake, contains areas of relatively strong radiometric anomalies (Charbonneau 1982). Granitoid intrusions adjacent or

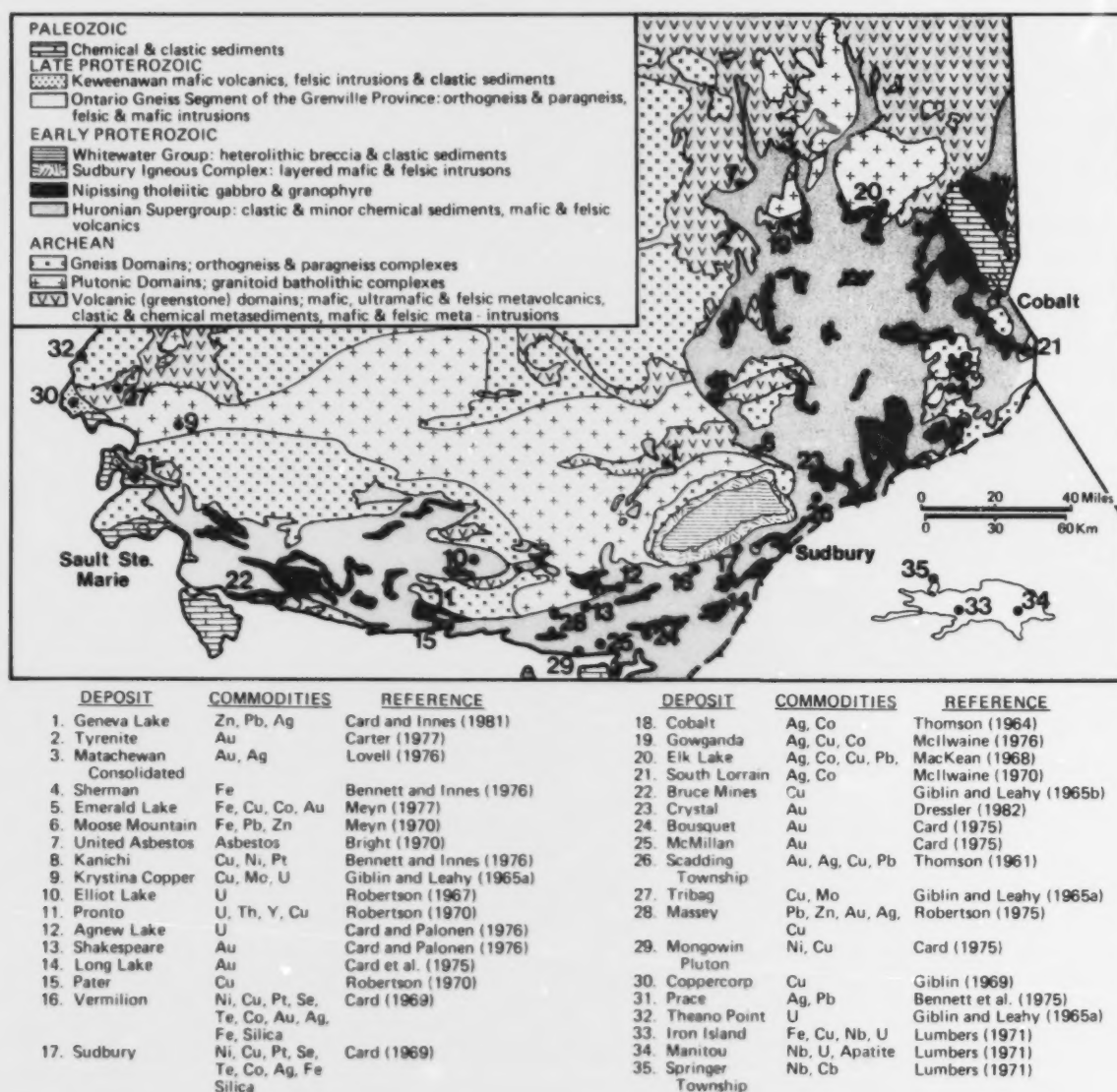


Figure 3.1. General geology and characteristic mineral deposits of the region encompassing Sudbury.

internal to "greenstone" sequences are a component in gold concentration.

Early Proterozoic Mineralization

HURONIAN SUPERGROUP

The Huronian Supergroup is a significant clastic sedimentary sequence that also contains extensive volcanic units and mafic intrusions in its lower part (Card *et al.* 1977). Each unit comprising the complex, possibly cyclical, depositional history of the Supergroup

has characteristic metal associations. Only the principal deposits are discussed in this section.

The largest and best known deposits are the uranium mines of the Elliot Lake area (Figure 3.1, #10). These occur in pyritic quartz-pebble conglomerates of the lower Matinenda Formation and are generally accepted to have been concentrated by placer processes in braided river systems (Robertson 1976). The Pronto Mine (Figure 3.1, #11) is an extension of this system and the Agnew Lake Mine (Figure 3.1, #12) is of similar style.

While analogies are commonly drawn between the Huronian in Ontario and the Witwatersrand in South Africa, as yet no major unequivocal paleoplacer gold concentrations have been located. The Shakespeare Mine (Figure 3.1, #13) in the Matinenda Formation and the Long Lake Mine (Figure 3.1, #14) in the Mississagi Formation (Mossman and Harron 1983) are possible examples, but both occur in areas of intense deformation and alteration.

The Huronian volcanic units contain relatively small copper deposits, several of which are proposed to be of the volcanogenic style (Pearson 1979) including the Pater Mine (Figure 3.1, #15). In addition, the Vermilion Mine (Figure 3.1, #16) hosted by mafic volcanic rocks of the Elsie Mountain Formation, is a chalcopyrite-pyrite orebody with recoverable Au-Ag-PGE.

NIPISSING DIABASE

A widespread intrusive event(s) of tholeiitic gabbro dikes and sills, termed the Nipissing-type diabase, followed deposition of the Huronian sequence and is dated at approximately 2150 Ma (Van Schmus 1965; Fairbairn *et al.* 1969). It is pervasive throughout the eastern Southern Province and locally intrudes the southern Superior Province and is possibly also represented in the northwestern Grenville Province (Lumbers 1975).

Two distinct types of mineralization associated with these intrusions are evident. The first consists of disseminated concentrations of Ni-Cu-PGE within the gabbros, and characteristic of magmatic segregation. While these are overshadowed by the younger Sudbury Igneous Complex deposits, significant concentrations are present in several locations (for example, Shakespeare, Sudbury Deposit, Figure 3.1, #17).

The second type of mineralization consists of mineralized quartz-carbonate veins, apparently open-space fillings, in or adjacent to the intrusions. The range of mineralization which is associated with these veins includes Au, Ag, Pb, Zn, Cu, Co, As, Bi, U, Ba, and Fe (Hematite). The best known example of the numerous deposits of this type which have been mined are the silver-cobalt deposits of the Cobalt Camp (Figure 3.1, #18). These have been mined continuously since discovery in 1903. Similar deposits are present in the Gowganda (Figure 3.1, #19), Elk Lake (Figure 3.1, #20) and South Lorrain (Figure 3.1, #21) Camps.

The first copper mine in Ontario, located at Bruce Mines (Figure 3.1, #22), was one of many which recovered copper from quartz-carbonate veins in this area. Similarly, there are numerous gold-bearing quartz veins of this type, typical examples being the Crystal (Figure 3.1, #23), Bousquet (Figure 3.1, #24), and McMillan (Figure 3.1, #25) Mines.

SUDBURY IGNEOUS COMPLEX AND WHITEWATER GROUP

The Ni-Cu-PGE deposits of the Sudbury Igneous Complex and the base-metal mineralization of the overlying Whitewater Group represent diverse types and styles. Even after 90 years of mining, exploration, and research, important new types and environments of mineralization are being discovered adjacent to traditional mining targets. All are the subject of extensive description in subsequent chapters of this volume and are not discussed here. They do, however, represent an integral part of the regional metallogenic development, and should be considered in that context.

MINERALIZATION OF YOUNGER OR UNDEFINED AGE

Within the regional context, metal enrichment was also produced by geological events other than those described above.

Breccia complexes of uncertain ages and origins, are common throughout the area; some of these are pipe-like and may have been formed by intrusive diatreme activity. The range of mineralization hosted by these complexes includes Au, Ag, Cu, Mo, and W.

The deposits of Scadding Township (Figure 3.1, #26) contain gold concentrations in a highly altered breccia within rocks of the Espanola and Serpent Formations (Harper 1983). Several similar gold-bearing breccias have been located northeast of Sudbury, south of Espanola, and east of Sault Ste. Marie.

The Tribag breccia deposits north of Sault Ste. Marie (Figure 3.1, #27) were mined for copper, but also host molybdenum and tungsten. Blecha (1974) suggested that these breccias were the product of porphyry-type activity associated with Keweenaw magmatism. The Massey Mine (Figure 3.1, #28), which produced copper from mineralized breccia, may also be related to diatreme activity.

Ultramafic to gabbroic rocks of the Mongowin Pluton (Figure 3.1, #29), dated at 1770 Ma (Van Schmus 1971), contain associated nickel sulphide mineralization. Keweenaw volcanism dated at approximately 1000 to 1050 Ma (Van Schmus *et al.* 1982) resulted in the introduction of copper, hosted by both volcanic and related sedimentary rocks (for example, Coppercorp Mine, Figure 3.1, #30) (Heslop 1970). Hydrothermal activity related to Keweenaw magmatism may also have been responsible for the concentration of Ag-Pb vein deposits around Sault Ste. Marie (for example, Prace Mine, Figure 3.1, #31) and possibly also uranium at Theano Point (Figure 3.1, #32).

A suite of alkalic and carbonatite complexes within rocks of the Grenville Province contains concentrations of Nb-Cb and REE (for example, Iron Island, Figure 3.1, #33; Manitou Island, Figure 3.1, #34; Springer Township, Figure 3.1, #35).

Metallogenetic processes are continuing even in the present day with gold placer concentrations of Quaternary-Recent age known in the Wanapitei and Vermilion River systems north of Sudbury.

DISTRIBUTION PATTERNS OF MINERALIZATION

The deposits described in the previous section are those which are traditionally considered of sufficient importance to be included in a description of the mineralization of this area. A substantial data base concerning the overall occurrence of mineralization is thereby excluded. In a metallogenetic, rather than an economic approach, every occurrence of relative concentration of metals is a contribution to the overall understanding of the development of mineralizing systems. This is, moreover, important from an economic standpoint. Restricting study to a historical perspective of what has already proven economically viable may preclude the recognition of the potential for mineralization of previously undiscovered types.

Initial study, by the authors, of the overall distribution of mineralization included deposits associated with Nipissing Intrusions, because of the large number of known mineral showings (in excess of 1000) of this association and the widespread occurrence of the intrusions. Card and Pattison (1973) postulated a rough zonation of metals which was subsequently better documented and defined (Innes and Colvine 1979).

Figure 3.2a shows the generalized distribution of metals associated with the Nipissing gabbros; the zones are based on distinct metal/mineral suites from which well-defined patterns are evident. The area around Sudbury is characterized by disseminated pyrrhotite, chalcopyrite, and pentlandite with platinum group elements within the gabbro bodies; locally, other sulphide and arsenide mineralization may be abundant, including millerite, cubanite, and gersdorffite. With distance from Sudbury, pentlandite and PGE content decrease; nickeliferous pyrrhotite is an intermediate nickel host as nickel content gradually decreases to background levels in sulphide phases.

As distance from Sudbury increases, vein mineralization predominates and occurs in or adjacent to gabbro intrusions and is not common where gabbros are absent. Westward, these veins are copper-bearing (chalcopyrite and bornite) and northeastward they

contain polymetallic base metals. Silver-cobalt arsenides with lesser nickel and copper characterize the Cobalt-Gowganda areas and there is a possible analogue around Sault Ste. Marie. Gold-bearing veins are prominent in specific areas, particularly around Sudbury and near Sault Ste. Marie. These data confirm and add substantially to the information gained from the larger deposits described earlier.

Such empirical patterns must have been the result of systematic geological processes. This has been the topic of hypothesis development and field study. A partial explanation of the apparent zonation around Sudbury may be found by an examination of the Nipissing Intrusions. Near Sudbury, the Intrusions are predominantly steeply dipping gabbros, but with distance they are generally more flat lying with granophyric phases common (Card and Pattison 1973). In addition, the metamorphic grade recorded in the intruded Huronian sequence is generally low, but reaches almandine amphibolite facies south and west of the Sudbury Igneous Complex. These features suggest a deeper level of crustal erosion near Sudbury and a possible centre or focus of intrusion there. This is consistent with the observed mineralization, with Ni-Cu-PGE concentrated by magmatic differentiation in the early sulphide fraction closer to the intrusive centre or at greater depth. The absolute amount of contained sulphide decreases along with a relative decrease in nickel and PGE content with distance from Sudbury consistent with the indicated upper or outer phases of the intrusive suite.

The remainder of mineralization in the area (Figure 3.2a) is characterized by open-space vein filling mineralization with a wide range of mono- or polymetallic deposits. Vein gangue also varies systematically from dominantly quartz near Sudbury to dominantly carbonate. This diverse range of metal and gangue types is not characteristic of the mafic intrusive affinity, but the close spatial association suggests a genetic link. It is, therefore, proposed that these deposits were formed by hydrothermal reconcentration of metals which were present in the wallrocks prior to intrusion. If this hypothesis has validity, evidence of such mineralization must be present in the rocks of the Huronian Supergroup which host the majority of the gabbros.

A compilation of mineral occurrences which appear to be directly related to the Huronian volcanic and sedimentary sequences was carried out to test this hypothesis. The data base is not so extensive as that of mineralization which is gabbro-related (more than 500 occurrences). This might be expected where mineralized occurrences typically consist of relatively low concentrations of sulphides distributed throughout the rocks, and therefore are not as prominent as the distinctive veins which were the traditional prospecting

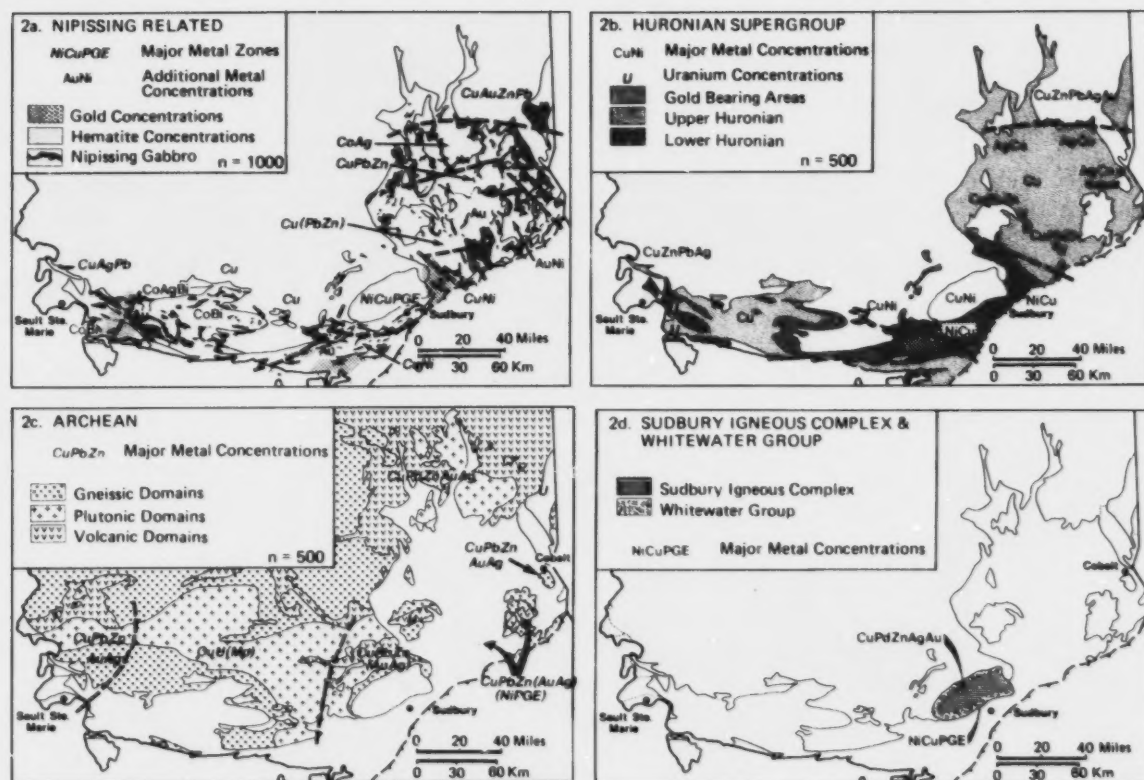


Figure 3.2. Characteristic zones of metal suites in the region encompassing Sudbury. 2a. Mineralization related to Nipissing gabbros. 2b. Mineralization in the Huronian Supergroup. 2c. Mineralization in the Archean basement. 2d. Mineralization in the Sudbury Igneous Complex and Whitewater Group.

targets. Nevertheless, there are clear patterns in Figure 3.2b which show a strong correlation with the gabbro-related patterns (Figure 3.2a).

Most of the Huronian deposits appear to be sedimentary or diagenetic in origin. An obvious example is the uraniferous quartz-pebble conglomerates of the Elliot Lake Camp. Less obvious are the sandstone- and siltstone-hosted copper and hematite deposits of the Desbarats, Flack Lake, Lady Evelyn, and Gowganda areas. In the Cobalt area, base-metal mineralization in conglomerates and siltstones of the Gowganda Formation is less well documented, but appears to be derived from a local source of mineralized volcanic basement. Nickel is present near Sudbury occurring in disseminated sulphides in volcanic rocks of the Salmay Lake and Stobie Formations.

Within the generalized areas, highlighted by the metal distribution patterns, specific styles and distribution of mineralization are largely controlled by sedimentary environments and restricted to specific lithostratigraphic units (Figure 3.3). An understanding of these factors provides a powerful geological tool for further exploration, in which paleoplacer gold and sedimentary copper are considered as prime targets.

A further step in hypothesis development, can be made by examining the Late Archean and Early Proterozoic geological framework. The only available provenance for Huronian clastic sedimentation was the Archean craton. The mineralization associated with these sedimentary rocks must, therefore, also have been derived from that provenance and, at least in part, reflect relative abundances in source area. Generalized paleocurrent trends (Figure 3.4) have a consistent southerly direction of sediment transport showing that the Archean craton to the north was the principal source of these sediments.

Characteristic Archean mineralization described earlier is generalized in Figure 3.2c, based on more than 500 deposit data points within or adjacent to the eastern Southern Province. Patterns reflect lithological type, granite-gneiss, "greenstone", or both. While we are obviously presently looking at post-erosion basement, derived sedimentary mineralization (Figure 3.2b) is strongly controlled by source abundance. Granitoid terrains contain occurrences of U, Cu, and Mo; the most prominent of these is the extensive Algoma Pluton to the north of the Huronian suite between Sault Ste. Marie and Sudbury. The upper phases of the pluton were probably the provenance for much

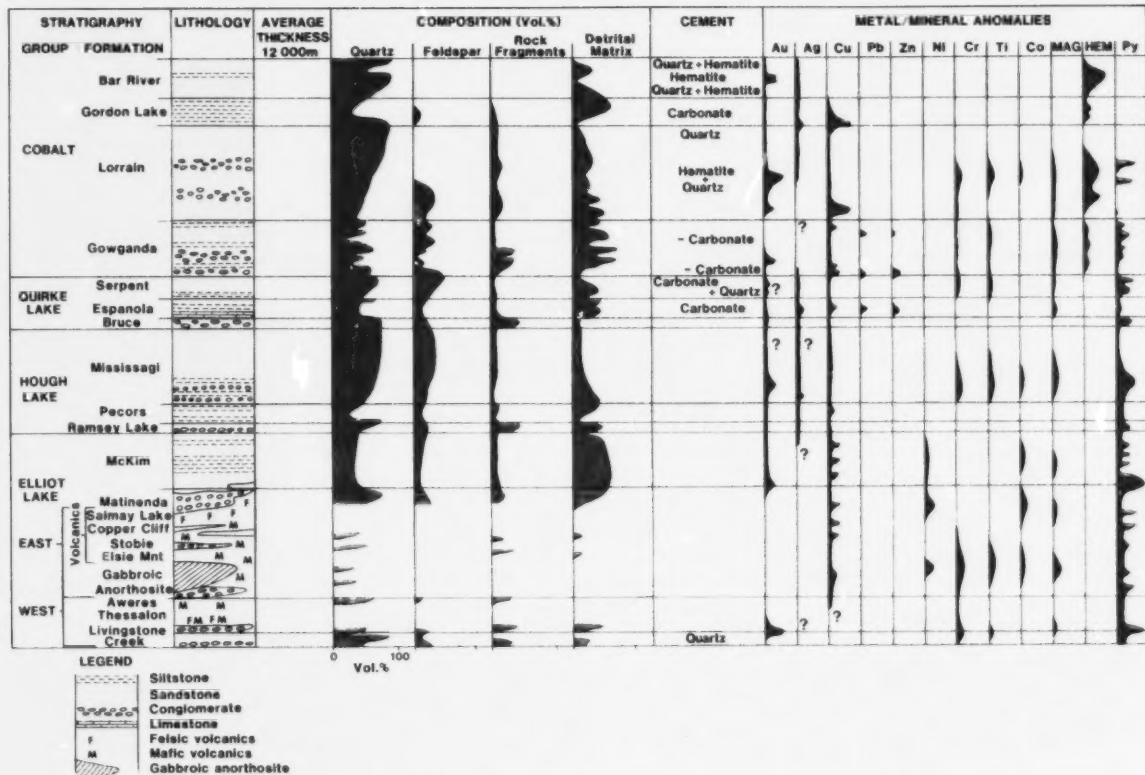


Figure 3.3. Stratigraphy, composition, and relative metal/mineral enrichment in the Huronian Supergroup.

of the sedimentation in this area (Robinson 1982). In the east, northeast, and extreme west, "greenstone" belts are present in provenance areas and this is reflected in a larger variety of derived sedimentary mineralization.

REGIONAL METALLOGENETIC MODEL

Within the Sudbury region, specific areas of the eastern Southern Province are characterized by relative abundance of mineralization. Patterns of mineralization appear to be time transgressive and, therefore, define metallogenetic zones or provinces which can be largely explained and modelled within the geotectonic framework of the area, as presently understood. Figure 3.5 shows a proposed comprehensive metallogenetic model for this area.

The Archean was a major period of primary introduction of metals into the crust. Redistribution of mineralization introduced during the Archean can be traced in the context of magmatic, sedimentary, and tectonic processes. Further episodes of metal introduction can also be identified.

In the Huronian, redistribution was mainly by sedimentary processes. Style of mineralization was

dependent on provenance, distance of transport, and prevailing sedimentary environment. Some mineralization represents true detrital concentration while other types may have formed during diagenesis, from migrating metal-bearing surface, ground, or intraformational waters.

A first stage in the processes of sedimentary concentration was uplift and erosion of the Archean cra-

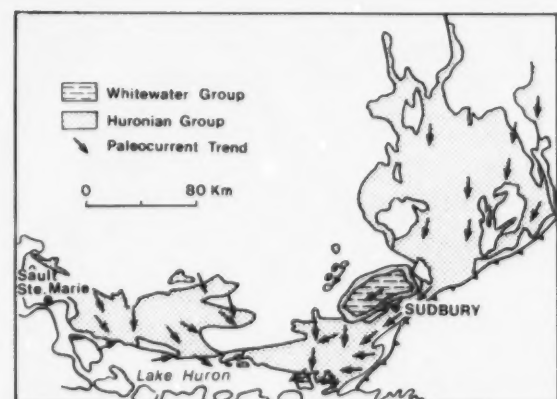


Figure 3.4. Generalized paleocurrent trends in the Huronian Supergroup and the Whitewater Group (from Sims *et al.* 1981).

tonic basement which itself may have been pre-enriched in some constituents by deep chemical weathering. Reworking of sediments in fluvial systems produced placer concentration of minerals, containing such metals as Au, Cu, U, Cr, Ti, and Fe. These minerals were able to withstand the multiple stages of reworking that allow concentrations to form at considerable distances from their source. Many base-metal sulphides and arsenides have more limited physical transport capability and concentrations of these are present only close to their source. Breakdown of such minerals could lead to solution transport in surficial or meteoric waters or composition fluids, with the potential for subsequent selective precipitation and concentration; climatic conditions, probably ranging from glacial to tropical and oxidation-reduction potentials are factors which controlled the transportational and depositional environments.

Tectonic activity exerted a primary control on Huronian sedimentation (Card *et al.* Chapter 2, this volume; Sims *et al.* 1981) and a strong correlation can be seen in the resultant mineralization where episodes of mineral enrichment are restricted in time and space. An active tectonic environment with vertical faulting produced the uplift for erosion and sequential hydraulic regimes necessary for developing placer and solution concentrations.

Huronian volcanism resulted in relatively minor metal introduction, and this principally consisted of copper and nickel. Gabbroic anorthosite intrusions, probably of Early Proterozoic age (Bennett and Innes 1976), also introduced Ni, Cu, PGE, Cr, and Ti into the system.

The Nipissing Intrusive Event(s) resulted in significant metal introduction, mainly Ni-Cu-PGE, and also caused considerable remobilization and reconcentration of metals which were present in their host rocks. In the latter system, 2 processes appear to have been operative;

1. a "heat engine" effect, best developed in argillite units, possibly as a result of the greater availability of water and also fracture response to intrusion
2. the assimilation of sedimentary rocks into the upper parts of sill-like gabbros, causing redistribution and concentration of mineralization. Assimilation may have been in part responsible for development of granophyric phases of the gabbroic intrusions.

The metallogenetic development of this region did not stop with the Nipissing Intrusive Event. The Sudbury Igneous Complex was formed approximately 290 Ma after emplacement of the Nipissing magmas; associated with this event is the largest known concentration of metals in the region, consisting principally of Ni-Cu-PGE (Figure 3.2d). Quartz-carbonate vein mineralization, of the style associated with the Nipissing Intrusions is absent from the Sudbury Igneous

Complex. The heterolithic breccias, argillites, and wackes of the Whitewater Group within the Sudbury Basin are also associated with a range of mineralization, including large volcanogenic-style base-metal deposits. Mineralized fragments in the Onaping Formation, discussed by Rousell (Chapter 9, this volume), are further evidence of pre-existing mineralization in the basement of the Sudbury Igneous Complex.

The series of geological events which have affected this region from the emplacement of the Sudbury Igneous Complex to the present day are associated with additional characteristic occurrences of mineralization representing both reconcentration of pre-existing metals and introduction of new mineralization into the system.

DISCUSSION OF METALLOGENETIC IMPLICATIONS

Metallogeny is only one aspect of a complete geological history, and comprehensive conclusions cannot be drawn from it in isolation. In addition, a discussion of the formation of the Sudbury Igneous Complex and its major ore deposits must follow the detailed descriptions which are contained in subsequent chapters. At this stage, however, some observations can be made concerning the location of the Sudbury Igneous Complex relative to its regional metallogenetic setting and also to Early Proterozoic metallogeny, worldwide.

REGIONAL SETTING

The area within an approximate 60 km radius of Sudbury is one of great geological complexity which has been affected by many events both pre- and post-formation of the Sudbury Igneous Complex.

Often, in a geologically active area, such events are associated with a large range of characteristic mineralizing processes. The diagrammatic representation of 4 main metallogenetic stages (Figure 3.5) must be linked with the major geotectonic stages outlined by Card *et al.* (Chapter 2, this volume) in order to evaluate Sudbury in the context of its complete metallogenetic setting.

It can be seen from Figures 3.2 and 3.5 that the Sudbury Igneous Complex was superimposed upon a localized Ni-Cu-PGE province, associated with at least 3 magmatic events which occurred over a period in excess of 600 Ma, prior to its formation. The major Ni-Cu-PGE deposits of the Sudbury Igneous Complex are, therefore, metallogenetically compatible with their setting on a local and regional scale.

GLOBAL SETTING

On a global scale, the Early Proterozoic is characterized by 4 major mineral deposit types:

1. Paleoplacers in clastic sediments; Au, U: e.g. Witwatersrand Basin
2. Magmatic segregations in layered mafic intrusions, PGE, Cr, Ni, Cu: e.g. Bushveldt Complex
3. Sedimentary or volcanosedimentary massive sulphides; Zn, Pb, Ag, Cu: e.g. Broken Hill and Mt. Isa
4. Superior-type hematitic iron formation; Fe: e.g. Minnesota Iron Range

All 4 types are represented in the Early Proterozoic rocks of the Sudbury region. Major deposits of the first type are present (Elliot Lake uranium deposits). While the Sudbury Igneous Complex is clearly not a typical layered mafic intrusive complex as discussed in subsequent chapters, it represents a major mafic magmatic event with associated Ni-Cu-PGE mineralization and it must also be considered in that context.

The Archean to Early Proterozoic period was characterized by a change in tectonic style from mo-

bile to cratonic in which extensional tectonics produced intracratonic rifting and marginal basin development (Windley 1981). The concomitant change in metallogenetic style has been discussed extensively (Hutchinson 1981a, 1981b). Paleoplacers and layered mafic intrusions are directly related to this change in tectonic style. Worldwide, the major mafic intrusive complexes in non-orogenic settings (Naldrett 1981) are largely restricted to this period of the Latest Archean and through the Proterozoic. Examples include:

Stillwater Complex	2750 Ma	De Paolo and Wasserburg (1979)
Concentrations of	Ni, Cu, PGE, Cr	
Great Dyke	2530 Ma	Allsopp (1965)
Major Reserves	Cr	
Concentrations of	Ni, Cu, PGE	
Bushveld Complex	2150-1920 Ma	Coertze <i>et al.</i> (1978)
Major Reserves	PGE	
Concentrations of	Cr, Ni, Cu, PGE	
Duluth Complex	1115 Ma	Faure <i>et al.</i> (1969)
Concentrations of	Ni, Cu, PGE	

While there is no standard type of intrusion and associated mineralization, the Sudbury Igneous Complex exhibits some differences in comparison to many of these Precambrian intrusions; the Sudbury Igneous Complex is more siliceous, the Ni-Cu-PGE mineralization occurs as a discrete unit at the base of the intrusion, and chromite concentrations are absent.

As discussed by Card *et al.* (Chapter 2, this volume), the developing Great Lakes Tectonic Zone played a role in controlling both magmatism and sedimentation. The Sudbury Igneous Complex formed across the northern margin of the developing tectonic zone. The younger Duluth Complex also formed adjacent to this tectonic zone, related to the Late Proterozoic mid-continent rift system (Sims *et al.* 1980; Sims *et al.* 1981) and is associated with extremely large concentrations of Ni-Cu-PGE; the average nickel and copper concentration is lower than that of mineralization of the Sudbury Igneous Complex, but the total contained metals in sulphide concentrations at the Duluth Complex are considerably higher than those of the Sudbury Igneous Complex (Bonnichsen 1974). On a larger scale, the mobile or orogenic zones peripheral to the Superior Province host additional concentrations of Ni-Cu-PGE, principally on the northwestern margin in Manitoba (Peredery *et al.* 1982) and the northern margin in Ungava. The major Ni-Cu-PGE deposits of the Sudbury Igneous Complex are, therefore, compatible with their regional tectonic setting, and also with characteristic Early Proterozoic metallogenetic processes.

SUMMARY

The superposition of many major geological events during the Archean and Proterozoic on the region en-

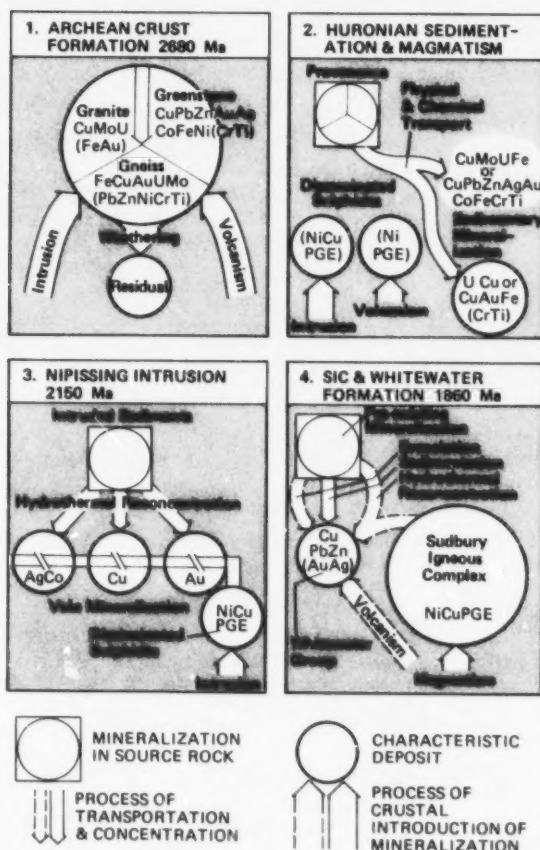


Figure 3.5. Metallogenetic model for the development of mineralization in the eastern Southern Province of Ontario.

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compassing Sudbury has controlled a variety of metallogenetic processes which formed a large range of important mineral deposits. By relating these processes to the sequence of geological events, a model has been developed which explains the occurrence of mineralization throughout the Early Proterozoic.

Subsequent chapters demonstrate that many of the immediate geological characteristics of the Sudbury Igneous Complex and its wallrocks cannot be readily explained as being consistent with normal or uniformitarian geological processes. This regional metallogenetic discussion is not intended to supercede these critical detailed descriptions and their evaluation. The metallogenetic data, however, clearly demonstrate that, whether the Sudbury Igneous Complex was formed as a result of normal, although not fully understood, geological processes, or was triggered by an external unique event, the mineralization represented at Sudbury is metallogenetically consistent with its location in time and space.

Major magmatic mineral deposits of similar metallogenetic style to the Sudbury Igneous Complex are largely restricted to this period of the Earth's history.

The Sudbury Igneous Complex occurs in an area which was a well-defined Ni-Cu-PGE metallogenetic province prior to its formation. This period of time lasted for approximately one quarter of the total recorded geological history of the area.

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CHAPTER 4

General Geology of the Sudbury Area

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ABSTRACT

The Sudbury Structure is at the "junction" of 3 structural provinces of the Canadian Shield; namely the Superior, Southern, and Grenville Provinces. Archean gneiss, metavolcanic and metasedimentary rocks, and granitic rocks of the Superior Province occur north of the Sudbury Igneous Complex. Early Proterozoic metavolcanic and metasedimentary rocks of the Huronian Supergroup occur mainly south and northeast of the Sudbury Igneous Complex. The granitic Creighton (2333 Ma), Murray (2388 Ma), and Skead Plutons, and the Nipissing gabbros (2150 Ma) intrude the Huronian rocks.

The Sudbury Igneous Complex (1849 Ma), is emplaced at the base of the Whitewater Group, which is a lithostratigraphic sequence of heterolithic breccias (Onaping Formation), mudstones (Onwatin Formation), and wackes (Chelmsford Formation). The rocks of the Onaping Formation are related to the origin of the Sudbury Structure, which is thought to be the result of either the impact of a meteorite or an endogenic explosion.

The ore deposits of the Sudbury area are found in the Sublayer, the Footwall, and the Footwall Breccia along the lower contact of the Sudbury Igneous Complex and in the so-called offsets.

Trap dikes are probably related to the Sudbury Igneous Complex and intruded it and the Footwall. Olivine diabase (1250 Ma) dikes are the youngest igneous rocks of the area.

High rank metamorphic rocks of the Grenville Province occur south of the Grenville Front Boundary Fault. The Archean gneisses north and east of the Sudbury Igneous Complex have been subjected to amphibolite to granulite facies regional metamorphism. Migmatites are common. The Huronian rocks south of the Sudbury Igneous Complex have been subjected to greenschist to amphibolite facies metamorphism. The rocks of the Whitewater Group in the Sudbury Basin and the Sudbury Igneous Complex itself exhibit greenschist facies mineralogy in the southern half of the Sudbury Structure, and subgreenschist facies mineral assemblages in the northern half. Shock-metamorphic features, including shatter cones, are

common in the Footwall rocks for as much as 10 km away from the Sudbury Igneous Complex and in the breccias of the Onaping Formation. The Wanapitei Lake Structure, interpreted in the literature to be an impact site, lies east of the Sudbury Igneous Complex.

INTRODUCTION

The Sudbury area is at the "junction" of 3 major geological subdivisions of the Canadian Shield; these are the Superior, Southern, and Grenville Provinces. All bedrock in the area is Precambrian in age (Table 4.1). Archean gneisses, metavolcanic-metasedimentary rocks, migmatites, and felsic and mafic plutonic rocks are unconformably overlain by Early Proterozoic metavolcanic and metasedimentary rocks of the Huronian Supergroup. The Archean and Huronian rocks form the Footwall of the Sudbury Igneous Complex. Felsic rocks of the Creighton, Murray, and Skead Plutons intrude the Huronian sequence south and east of the Sudbury Igneous Complex. Nipissing gabbro, also of Early Proterozoic age, is widespread in its occurrence.

The Sudbury Structure as defined in this volume consists of

1. breccias in the Archean and Proterozoic Footwall rocks of the Sudbury Igneous Complex
2. the Whitewater Group, consisting of the Onaping, Onwatin, and Chelmsford Formations
3. the Sudbury Igneous Complex

Post-Igneous Complex mafic dike rocks, the so-called "trap" dikes, are found mainly in the South Range of the Igneous Complex and South Range Footwall rocks, and are possibly related to the Complex itself. Middle Proterozoic olivine diabase dikes intrude all the foregoing rocks.

Southeast of the Sudbury Structure and south of a major northeasterly-trending tectonic zone, the Grenville Front Tectonic Zone, high rank metamorphic gneisses of the Grenville Province have experienced a complex geological history. These rocks are Middle to Early Proterozoic in age.

Archean gneisses north of the Sudbury Igneous Complex in the vicinity of the Town of Levack were affected by amphibolite to granulite facies metamorphism. The age for this high rank metamorphic event is not known, but it is considered to be of Archean age and to be older than the emplacement of most felsic plutons in the area. In the Early Proterozoic, renewed tectonism led to crustal foundering and deposition of the Huronian Supergroup.

The northern parts of the Sudbury Igneous Complex and the Whitewater Group are almost unmetamorphosed. The southern parts of these units, the

Huronian rocks, the felsic plutons south of the Sudbury Igneous Complex, and the Nipissing gabbro, however, were affected by low to middle rank Early Proterozoic metamorphism. Contact metamorphic effects are present in narrow zones around the Sudbury Igneous Complex.

Shock-metamorphic features in the Footwall rocks and fragments in the breccias of the Onaping Formation are related to the Sudbury Event. This event was either caused by an endogenic volcanic process or was caused by a meteorite impact.

Southeast of the Sudbury Structure, and south of the major northeast-trending Grenville Front Tectonic Zone, the rocks reflect a complex history of metamorphic events. Regional metamorphism in the Grenville Province probably accompanied the emplacement of Early Proterozoic felsic plutons. Middle Proterozoic high rank regional metamorphism occurred having a temperature of at least 650° to 750°C, and an operative pressure of 6 to 9 kb (Lumbers 1975). Retrograde metamorphism accompanied later deformation along the Grenville Front Tectonic Zone.

The geology of the area covered by the Sudbury geological compilation map at a scale of 1:50 000 (Map 2491, back pocket), is described on the following pages. This compilation map and also much of the following descriptions are based on the work of many researchers whose contributions are listed in the legend of the map. Some lithological units are described in more detail than others. In the more detailed accounts, new data is presented that is not covered elsewhere in this volume.

General Geology

Superior and Southern Provinces

ARCHEAN

Granodioritic-Quartz Dioritic Gneisses and Associated Mafic Rocks

Grey, banded gneisses of granodioritic, tonalitic to quartz dioritic composition of Archean age in many places, form the Footwall to the Sudbury Igneous Complex. Associated with these gneisses are mafic rocks, granitic gneisses, and various amounts of anatectic mobilizate. These rocks are most common northwest of the Igneous Complex where they were termed "Levack gneisses" and were grouped together in the "Levack Complex" (Langford 1960). Such rocks may underlie large parts of the Sudbury Igneous Complex.

These gneisses have very inhomogeneous compositions and textures. Compositional layering is

CHAPTER 4

TABLE 4.1: PRECAMBRIAN LITHOSTRATIGRAPHY, SUDBURY AREA.

	GRENVILLE PROVINCE	SOUTHERN PROVINCE	SUPERIOR PROVINCE
MIDDLE PROTEROZOIC	Mafic to Ultramafic Stocks* Late Pegmatite (900-1100 Ma) High rank regional metamorphism Late Mafic Intrusive Rocks* Anorthosite Suite Intrusive Rocks (1200-1500 Ma)	Olivine Diabase (1250 Ma)	Olivine Diabase (1250 Ma)
EARLY PROTEROZOIC	Early Pegmatite (1600-1700 Ma) Granitic Intrusive Rocks (1590-1700 Ma)	S U S Trap Dikes* D T Intrusive Contact B R Sudbury Igneous Complex U U Sublayer** C Intrusive Contact Y T Main Mass (1849 Ma) ← Gabbro* (Basin Interior) U Whitewater Group R Chelmsford Formation E Onwatin Formation Onaping Formation ← Sudbury Breccia Footwall Breccia shock metamorphism Sudbury Event	
	Early Mafic Intrusive Rocks* (some younger than Granitic Intrusive Rocks) Intrusive and Metamorphic Contact Metasedimentary Rocks	Nipissing Intrusive Rocks (2160 Ma) Intrusive Contact Creighton, Murray and (?) Skead Plutons (2333 Ma) Intrusive Contact Huronian Supergroup Unconformity Archean Superior Province-style basement	Diabase* Intrusive Contact Mafic Plutonic Rocks and Anorthosite Intrusive Contact Migmatite and Felsic Plutonic Rocks (2500-2600 Ma) Intrusive and Metamorphic Contact Metavolcanic and Metasedimentary Rocks Granodioritic - Quartzdioritic Gneisses and Associated Mafic Rocks
ARCHEAN			

* Absolute age unknown

* Age relationship to Late Pegmatite not known

** Absolute age unknown. pre-Main Igneous Complex phases may exist too

prevalent in all the gneisses (Photo 4.1), with individual units ranging in thickness from a few mm to several 10s of m. Most of the gneisses are medium grained and grey. Pinkish varieties and fine-grained varieties also occur. Dark grey to black mafic layers 10 cm to a few m thick occur in Levack Township, and, in places (map unit 1b on the Sudbury compilation map; Map 2491 back pocket), make up more than 50% of the Gneiss Complex.

In some places, such as in southern Levack Township, the gneisses exhibit granulite facies mineralogy. In other places, such as in northern Levack Township, amphibolite facies mineralogy is present. The metamorphic mineral assemblages of the Levack gneisses are listed in Table 4.5. Retrograde metamorphism,

and, near the Sudbury Igneous Complex, contact-metamorphic overprinting are common.

The amphibolite facies gneisses are more common than the granulite facies gneisses, and, in Levack Township, occur farther away from the Sudbury Igneous Complex. These rocks appear to be more inhomogeneous texturally than the granulite facies gneisses, and exhibit blastomylonitic and perlitic rock textures as well as the more common equigranoblastic textures.

The mafic layers are conformable with the gneissosity and the compositional layering of the tonalitic, granodioritic-quartz dioritic rocks. In places, the mafic layers are strongly boudinaged. The mafic rocks are common in Levack Township for as much as 1 km



Photo 4.1. Banded, granodioritic "Levack Gneiss" with 1 mafic band.

away from the Sudbury Igneous Complex. According to Doucet (1981), the mafic rocks are composed of augite (4 to 51%), hypersthene (as much as 24%), hornblende (as much as 82%), biotite (1 to 32%), plagioclase (as much as 49%), and accessory minerals such as apatite, zircon, and opaque minerals.

The Levack Gneiss Complex, in many places, contains some granitic to quartz dioritic mobilizate. Homogeneous, not banded, somewhat gneissic rocks of quartz dioritic composition, Langford's (1960) tonalites, are regarded by the author to be diatectic in origin.

The compositional layering of the rocks suggests that the Levack Gneiss Complex originated from a supracrustal sedimentary-volcanic or layered-intrusion protolith. The author believes that the great compositional variations, such as that of the quartz content in the gneisses, support the idea that the Levack Gneiss Complex, and possibly most of the similar gneisses of the North Range Footwall, represent a metamorphosed sequence of clastic sediments, minor mafic to ultramafic volcanic rocks, and possibly minor felsic volcanic rocks. The Complex as a whole, therefore, is probably not meta-igneous in origin. In a few places, minor gabbro and anorthositic gabbro bodies occur in areas underlain by the Levack Gneiss Complex and were also intersected by diamond drilling at the Strathcona Mine near the Town of Levack (Falconbridge

Limited, Geological Staff, personal communication, 1982). These "minor" bodies are not considered by the author to be part of the Levack Gneiss Complex proper.

The metamorphic grade and appearance of these "Levack Gneisses" differ greatly from the lower metamorphic grade Archean metavolcanic-metasedimentary "greenstones" north and northeast of the Sudbury Igneous Complex. This suggests that the gneisses of the Levack Gneiss Complex represent the oldest rocks in the area covered by the Sudbury compilation map (Map 2491, back pocket).

The gneisses may underlie large parts of the Sudbury Igneous Complex.

Metavolcanic-Metasedimentary Rocks

Archean metavolcanic rocks and associated metasedimentary rocks are exposed northwest and northeast of the Sudbury Igneous Complex. Northwest of the Complex, the easternmost section of the Benny Belt (Card and Innes 1981) is exposed in the area covered by the Sudbury compilation map (Map 2491, back pocket). In Hutton and Parkin Townships, northeast of Sudbury, a metavolcanic-metasedimentary sequence has been mapped by Meyn (1970). Metavolcanic-metasedimentary remnants, from < 1 m to several hundred m in size also form inclusions within the Archean felsic plutonic rocks. This indicates a wide original distribution of the volcanic-sedimentary rock units north of the Sudbury Igneous Complex. The following description of the Archean metavolcanic-metasedimentary rocks is based mainly on the work of Card and Innes (1981) with minor additional observations by Meyn (1970) and Dressler (1982).

The Benny Belt is approximately 38 km long and has an average width of 2.4 km. The belt is bordered by Archean felsic plutonic rocks to the north and south. Eastward, the belt gradationally passes into migmatitic rocks where the volcanic and sedimentary rocks were metamorphosed under greenschist to amphibolite facies conditions and were intruded and assimilated by mobile granitic material.

The Benny Belt is characterized by distinct longitudinal facies variations. The western part, that part west of the area covered by the Sudbury compilation map (Map 2491, back pocket), is underlain mainly by tholeiitic and calc-alkalic metabasalts and metagabbros. The central parts of the "greenstone" belt consist of several cyclically repeated calc-alkalic and minor tholeiitic mafic, intermediate, and felsic units. The eastern sector is composed mainly of calc-alkalic andesite to rhyolite tuff-breccia and lapilli-tuff.

The Benny Belt is considered by Card and Innes (1981) to be a homoclinal sequence facing south. In Figure 4.1, two generalized lithological sections across the eastern part of the Benny Belt are shown.

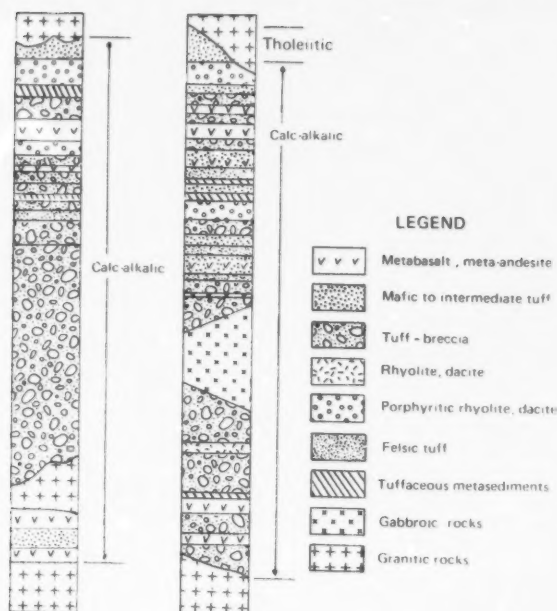


Figure 4.1. Generalized lithological sections across the eastern part of the Benny Belt (from Card and Innes 1981).

Figure 4.2 shows a cation diagram for the metavolcanic rocks.

The Archean metasedimentary rocks of the Benny Belt consist of metamorphosed wacke, siltstone, graphitic siltstone, and chert. Minor quartz-feldspar arenite and an oxide facies iron formation unit also occur. The metasedimentary units are interstratified with the metavolcanic rocks and occur as units commonly 15 to 30 m thick, and are rarely up to 60 m thick. Copper, lead, and zinc sulphide minerals are associated with the more common pyrite and pyrrhotite mineralization. The sulphide minerals are stratabound, and commonly are at the contacts of mafic flow and pyroclastic units with felsic to intermediate pyroclastic rocks.

The rocks of the Benny Belt have been metamorphosed under greenschist to amphibolite facies conditions. Most lithologies are strongly deformed. Flattened rock fragments and pillows, a penetrative foliation with a down-dip rodding lineation, and many faults and minor folds occur throughout the "greenstone" belt.

In Parkin and Hutton Townships (Meyn 1970), northeast of Sudbury, the volcanic-sedimentary lithologies are similar to the Benny Belt lithologies. In contrast to the Benny area, where no economic iron deposits are known, several oxide facies iron formation deposits have, until recently, been exploited at the Moose Mountain Mine in Hutton Township. Iron for-

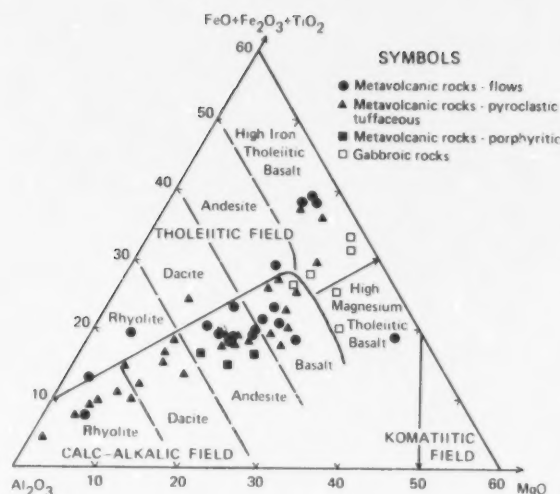


Figure 4.2. Cation plot of metavolcanic rocks, Benny Belt (from Card and Innes 1981).

mation and other Archean rocks also occur northwest of Lake Wanapitei (Dressler 1982). The same lithologies also underlie part of the terrain presently occupied by the Sudbury Structure; these occur as fragments in the Footwall Breccias (Dressler, Chapter 6, this volume) and the Onaping Formation (Muir and Peredery, Chapter 7, this volume).

Felsic Intrusive Rocks

Massive felsic intrusive rocks underlie much of the terrain extending from Agnew Lake, southwest of the Sudbury Igneous Complex, around the North Range of the Complex to about the position of Bowlands Bay in Wanapitei Lake which lies to the east of the Sudbury Igneous Complex. These rocks form part of the Cartier Granite or Cartier Batholith (Card and Innes 1981). Near Agnew Lake, a felsic pluton was termed Birch Lake Granite or Birch Lake Batholith (Card and Palonen 1976). These 2 batholiths are mesozonal, composite plutons that belong to the "Algonian Granites" emplaced 2500 Ma or more ago (Van Schmus 1965).

Texturally, the felsic rocks are equigranular, and in places are porphyritic and commonly non-foliated. Rapakivi textures were observed by Card and Innes (1981). In Hart, Ermatinger, and Totten Townships, Choudhry (formerly Geologist, Ontario Geological Survey, personal communication, 1982) mapped the contact of the Birch Lake Granite which is medium-grained, equigranular, in places foliated and somewhat altered. He concluded that the Birch Lake Granite is probably older than the Cartier Granite which is coarser grained, in many places, porphyritic, and is unaltered. Similar observations were made by the au-



Figure 4.3. Modal composition of Archean granitic rocks. Q—quartz, A—alkali-feldspars, P—plagioclase.

thor (Dressler 1980) in Emo, Rhodes, and Botha Townships, a few km northwest of the area covered by the Sudbury compilation map (Map 2491, back pocket), where porphyritic granites intrude older, medium-grained, equigranular felsic plutonic rocks.

The felsic intrusive rocks are medium to coarse grained, pink or grey, and range in modal composition from granite to granodiorite and minor tonalite (Figure 4.3). Biotite and/or hornblende make up as much as 15% of the rocks, but on average constitute 2 to 4% of the rocks. Accessory minerals are muscovite, titanite, zircon, and iron oxide minerals. The plagioclase is commonly an oligoclase, and in many places is partly saussuritized. Secondary chlorite and epidote are common.

Fine- to medium-grained aplite and coarse-grained pegmatite are common in all felsic plutonic rocks and are also common in Archean gneisses and metavolcanic-metasedimentary rocks. These older Archean supracrustal rocks also occur as inclusions in the plutonic rocks.

Migmatites

Migmatites occur west, north, and east of the Sudbury Igneous Complex and commonly border terrains underlain by Archean gneisses and metavolcanic-metasedimentary rocks. The migmatites occur also within areas underlain predominantly by granitic rocks and represent remnants of formerly more extensive gneiss or metavolcanic-metasedimentary units.

All the common migmatite structures were observed in the Archean migmatites that compose part of the Footwall of the Sudbury Igneous Complex. Meta-

textites are more common than diatexites, and exhibit breccia, net and raft structures, or are layered and veined. Schlieren and nebulitic structures form transitions to inhomogeneous to scarce homogeneous diatexites in which the paleosome is no longer recognizable.

The mobilizates have a granitic, granodioritic to quartz dioritic composition, are medium grained, coarse grained, or are pegmatitic, and range in colour from red to pink and white.

All gradations exist from gneisses and metavolcanic-metasedimentary rocks to granites. The granitic mobilizate of the migmatites is, therefore, probably partly magmatic-intrusive, and in part are anatectic, and/or hybrid.

Mafic Plutonic Rocks and Anorthosite

Gabbroic rocks occur in several places within the Footwall of the Sudbury Igneous Complex. Most occurrences lie close to the Sudbury Igneous Complex. These rocks have probably been brought to their present position by the Sudbury crater-forming event. Anorthosite bodies occur at the base of the Huronian sequence in Drury, Hyman, and Falconbridge Townships.

The gabbroic rocks are medium to coarse grained, and are dark greenish grey to black. These rocks are commonly coarser grained than the Early Proterozoic Nipissing gabbros, and in a few places, are intruded by diabase dikes (*see* section on "Nipissing Intrusive Rocks", this article). Primary rock forming minerals, such as pyroxene and plagioclase, are commonly completely altered to actinolite and saussurite. Near the Sudbury Igneous Complex, contact metamorphic recrystallization has led to the growth of clinopyroxene, hornblende, and clear, very fine grained decussate plagioclase.

The anorthosite bodies at the base of the Huronian Supergroup range in thickness from 30 to 900 m in Drury and Hyman Townships (Card *et al.* 1977) to approximately 750 to 2000 m in Falconbridge Township.

The relative age of the anorthosite bodies is a matter of debate. The rocks have not been dated radiometrically, and Card *et al.* (1977) stated that the intrusions occur at the base of the Huronian metavolcanic sequence and locally intrude Huronian metasedimentary rocks. The author remapped a small area in Hyman and Drury Townships, and studied the anorthosite in Falconbridge Township. The author, based on these observations, cannot substantiate the interpretations made by Card *et al.* (1977). In Drury and Falconbridge Townships, the anorthosite was found to be intruded by diabase dikes identical in appearance to diabase dikes in the granitic terrain nearby. The radio-

metric age of these diabase dikes also is not known, but the dikes were not found to intrude the Huronian sequence. Furthermore, in Drury Township, just south of the Chicago Mine, a Huronian conglomerate located just west of Highway 658 and containing coarse-grained anorthosite clasts appears to overlie the anorthosite. Therefore, the Gabbro-Anorthosite Intrusions probably are Late Archean or pre-Huronian Early Proterozoic in age¹.

The intrusive bodies range in composition from gabbro to anorthositic gabbro and gabbroic anorthosite. Minor trondhjemitic and syenitic segregations also occur.

All these rocks are coarse grained or very coarse grained (Photo 4.2) and consist of saussuritized plagioclase, and bluish green hornblende and actinolite after pyroxene. Magmatic layering is 0.5 to 100 m thick, and is defined by compositional and textural variations. Chemical plots (Card *et al.* 1977) show that most of the gabbro-anorthosite rocks are subalkalic and tholeiitic. A cation plot of the analyses by Card *et al.* (1977) is shown in Figure 4.4.

Diabase

Metamorphosed mafic dike rocks intrude the Archean felsic plutonic and older rocks, as noted above and also the gabbro-anorthosite suite rocks in Drury, Hyman, and Falconbridge Townships, but not the sedimentary and volcanic rocks of the Huronian Supergroup. These dike rocks are therefore Late Archean or Early Proterozoic in age.

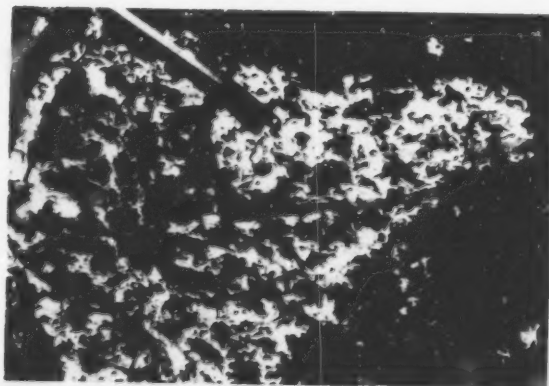


Photo 4.2. Coarse-grained anorthosite cut by Sudbury Breccia. Chicago Mine, Drury Township.

¹The gabbro at East Bull Lake (a Gabbro-Anorthosite Intrusion) has an age of 2480 Ma (T. Krogh, Geochronologist, Royal Ontario Museum, personal communication, 1983). This indicates an Early Proterozoic age for this intrusion, and possibly also for the Gabbro-Anorthosite Intrusions near Sudbury (see Krogh *et al.*, Chapter 20, this volume).

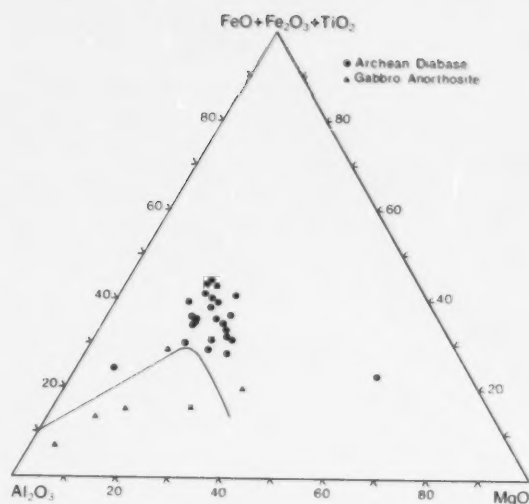


Figure 4.4. Cation plot of gabbro-anorthosites (solid triangles) at the base of the Huronian Supergroup and of diabase dikes (solid circles). Data from published and unpublished Ontario Geological Survey reports.

The mafic dikes range in thickness from approximately 20 cm to 30 m, and in many places form swarms of parallel dikes. North of the Sudbury Igneous Complex, dike sets commonly strike north-west, whereas southwest of the Complex, in addition to northwestern striking directions, there are east-striking and northeast-striking dikes. The east-striking dikes parallel the trend of a pre- to early Huronian east-striking graben system (Card *et al.*, Chapter 2, this volume) and possibly represent feeders for the mafic volcanic rocks of the lower Huronian Supergroup.

Most of the dikes are dark green to black, fine grained, and equigranular. Plagioclase porphyritic and glomeroporphyritic varieties also occur. All dike rocks exhibit a common metagabbroic mineralogy of plagioclase, actinolitic hornblende, biotite, with minor quartz, epidote, chlorite, titanite, epidote, iron oxides, and sulphide minerals. Chemically, analyses of the rocks plot in the iron tholeiitic basalt field of a cation plot (Figure 4.4).

EARLY PROTEROZOIC

Huronian Supergroup

The Huronian Supergroup is an Early Proterozoic assemblage of volcanic and sedimentary rocks that forms part of the Penokean Fold Belt of the Southern Province in Ontario. The sequence was deposited between about 2500 Ma ago and 2150 Ma, the Rb-Sr radiometric age of the Nipissing Intrusive Rocks (Van Schmus 1965; Fairbairn *et al.* 1969). Southwest of the Sudbury Igneous Complex in the Sudbury-Espanola

area, the Huronian Supergroup has a total thickness of over 10 700 m (Card *et al.* 1977). Northeast of the Complex, in the Wanapitei Lake area, it has a total cumulative thickness of approximately 8000 m (Dressler 1982).

The Huronian sedimentary sequence is characterized by cyclical repetitions of conglomerate, mudstone, and wacke, and quartz-feldspar arenites. Based on this cyclicity, the Huronian Supergroup is subdivided into 4 groups, namely the Elliot Lake, Hough Lake, Quirke Lake, and Cobalt Groups. Volcanic rocks occur only in the lowermost group, the Elliot Lake Group. The volcanic rocks consist of subalkalic, tholeiitic, mafic, and felsic flows and pyroclastic rocks.

Poorly sorted quartz-feldspar arenites occur in the Matinenda Formation, the lower Mississagi Formation, Serpent, and Lorrain Formations in the area covered by the Sudbury compilation map (Map 2491, back pocket). These rocks represent a milieu where rapid deposition occurred in a high energy environment. The Upper Mississagi Formation, and the Serpent and Lorrain Formations are characterized by submature to mature arenites deposited in an environment, where, in contrast to the lower sections of the formations, winnowing was moderate or strong (Card 1978a). The finer grained detritus was deposited locally, or farther away, mainly south and southwestward down the paleoslope.

McDowell (1957) proposed a fluvial origin for the Mississagi Formation quartz-feldspar arenites of the Blind River area. Mudstones and wackes of the Middle Mississagi Formation represent a marine submergence or a large lake (McDowell 1957). Frarey and Roscoe (1970) also suggested a fluvial or fluvial-deltaic origin for the Huronian arenite units. Casshyap (1971) described the Mississagi and Serpent deposits in the Espanola-Willisville area and considered the deposits to be fluvial-deltaic in origin. The Gowganda Formation arenites he considered to be prograding deltaic deposits, and the Lorrain Formation he considered to be deltaic, beach, and marine deposits. According to Palonen (1971, 1973), the Mississagi Formation sandstones in the Elliot Lake area represent a generally regressive sequence deposited in a tidal flat environment. South of Elliot Lake, the Mississagi Formation is interpreted to be a marine shelf deposit. Long (1976) considered the Mississagi and Serpent Formations to have been deposited in fluvial environments, principally from bedload and mixed load streams. According to Long (1976), paleocurrent and petrographic trends indicate that 2 major regional braided river systems existed during the deposition of the rocks that comprise the Mississagi and Serpent Formations. One of these systems flowed east and south from the Sault Ste. Marie-Elliot Lake region to meet another southwesterly flowing system originat-

ing in the Cobalt Embayment northeast of the Sudbury Structure. Card (1976) suggested that the mature quartz arenites and quartz-feldspar arenites of the Lorrain Formation represent nearshore coastal shelf environments and that they were laid down during cyclically repeated marine transgressions and regressions.

Wackes and mudstones occur mainly in the McKim, Pecors, Espanola, and Gowganda Formations. These rocks are immature, poorly sorted, or unsorted rocks deposited below wave base. Some rocks in these formations were deposited by turbidity currents. Thinly laminated wackes of the Gowganda Formation possibly represent varves.

The Espanola Formation contains the only major development of carbonate rocks in the Huronian succession. Limestone and dolostone occur either as thin interbeds in mudstone and wacke, or form laminated and pure carbonate beds up to 15 m thick. The Limestone Member of the Espanola Formation (Card 1978a) in the Sudbury-Manitoulin area is up to 60 m thick. Northeast of Sudbury, large areas appear to be underlain by rocks of the Espanola Formation (Dressler 1982; Sudbury compilation map, Map 2491, back pocket). The outcrop density of the Espanola Formation northeast of Sudbury, however, is poor, and no reliable estimate of the thickness of the formation is possible. At Quirke Lake, near Elliot Lake, stromatolites in the Espanola Formation (Hofmann *et al.* 1980) indicate local depositional conditions stable for time periods long enough to allow the growth of benthic organisms. Limestones with fine laminae resembling algal mats were observed by the author in the Espanola Formation in Street Township east of Sudbury.

The Ramsay Lake, Bruce, and Gowganda Formations contain conglomerates that, in general, are polymictic and unsorted, or are poorly sorted. The conglomerates range in composition from orthoconglomerate to pebbly wacke. Several workers have suggested a glacial or marine-glacial origin for these rocks (Coleman 1905a, 1905b; Casshyap 1969; Young 1970; Lindsey 1971). Pebbly wackes are characterized by "dropstones" that probably represent ice-rafted fragments which have been dropped into fine-grained, muddy wackes from floating ice. Legun (1984) interpreted the Gowganda Formation rocks of the Cobalt area to have been deposited in a glaciolacustrine valley environment below an ice shelf, similar to deposition in the present Antarctic (Drewry and Cooper 1981). Parviainen (1973) considered the Ramsay Lake and Bruce Formations to have been deposited as land-laid tills. The glacial origin of all of the Huronian conglomerates, however, is not undisputed. Card (1978a), for instance, stated that glaciation may have initially supplied coarse detritus to the depositional basin. Subsequent redeposition by

turbidity currents and debris flows then may have played an important role.

Volcanic rocks occur in the Elsie Mountain, Stobie, and Copper Cliff Formations of the Elliot Lake Group. Most of the Elsie Mountain and Stobie volcanic rocks are tholeiitic, massive, or pillowed basaltic flows with minor basaltic pyroclastic rocks and very minor felsic to intermediate flows. The Copper Cliff Formation consists of rhyolitic to dacitic flows or sub-volcanic intrusions and minor pyroclastic rocks. In a few places, basalts are also found in the Copper Cliff Formation. Chemical data (Figure 4.5) in general show a tholeiitic iron-enrichment trend for all the volcanic rocks of the Huronian Supergroup in the Sudbury area.

Table 4.2 shows 3 generalized stratigraphic sections of the Huronian Supergroup. The first section in this table is a composite section after Card *et al.* (1977) with minor modifications by the author. The section of Card *et al.* (1977) represents the Huronian Supergroup west of the City of Sudbury in the Sudbury-Espanola area. The Gordon Lake and Bar River Formations of the Cobalt Group were omitted by the author from the section of Card *et al.* (1977) because these formations appear to be absent from the present study area. The anorthosite bodies shown by Card *et al.* (1977) as part of the Huronian Supergroup at the base of the succession were omitted because they are probably pre-Huronian in age (*see* section on "Mafic Plutonic Rocks and Anorthosite", this Chapter).

The second section of Table 4.2 is based on reconnaissance investigations by the author in Falconbridge and Street Townships east of Sudbury. There, the Huronian succession appears to be incomplete. The third

section, representing the Huronian just north of Wanapitei Lake, is based on investigations by the author (Dressler 1981, 1982), and is characterized again by the absence of some formations and by the great range in thicknesses of individual formations.

Primary sedimentary and volcanic structures are also listed in Table 4.2. A few of these structures are shown in Photos 4.3 to 4.7.

Creighton, Murray, and Skead Plutons

Three Early Proterozoic granitic plutons occur along the South Range of the Sudbury Igneous Complex; from west to east these are the Creighton, Murray, and Skead Plutons. The Creighton and Murray Plutons may be parts of a larger granitic body and be connected at depth. A former connection between the 2 plutons may once have existed above the present level of exposure (Dutch 1979). The Murray Pluton may represent a higher level intrusion than the Creighton Pluton because it is commonly finer grained than the latter.

The Creighton and Murray Plutons intrude the rocks of the Huronian Supergroup and several apophyses appear to extend outward from the main masses of these plutons into the Huronian rocks. Inclusions of Huronian metavolcanic and metasedimentary rocks are also present within the granitic rocks and range in size from a few cm to 8 km. Card (1978a) has described potassic feldspar porphyroblasts in country rocks near the Creighton Pluton. All these observations prove the Creighton and Murray Plutons to be post-Huronian in age. The relative age of the "granites" and the Sudbury Igneous Complex, however, has been a matter of debate. Field evidence exists for both a pre- and a post-Sudbury Igneous Complex age for the granitic plutons. Yates (1938) and Burrows and Rickaby (1935) pointed to granitic dikes, similar to the Creighton and Murray Plutons, that intrude the Sudbury Igneous Complex north of the main masses of the plutons, and concluded that the "granites" are younger than the Sudbury Igneous Complex.

Evidence for a pre-Sudbury Igneous Complex age for the granitic plutons includes: alteration and impregnation with sulphide minerals of the granites at their contacts with the Sudbury Igneous Complex; Sudbury brecciation of the granitic rocks; the cross-cutting relationship of the Copper Cliff Offset with the Creighton Pluton; and radiometric age determinations. Krogh *et al.* (1982) obtained a U-Pb zircon age of 1849 Ma for the norite of the Sudbury Igneous Complex. Gibbins *et al.* (1972) published a Rb-Sr isochron age of 2230 Ma for the Main Mass of the Murray Pluton and an age of 2050 Ma for the Murray Offshoot, a granitic dike that intrudes the norite in the vicinity of the Little Stobie Mine. The Creighton Pluton has been dated at 2333 Ma (U-Pb zircon; Frarey *et al.* 1982). The Murray Pluton is dated at 2388 Ma

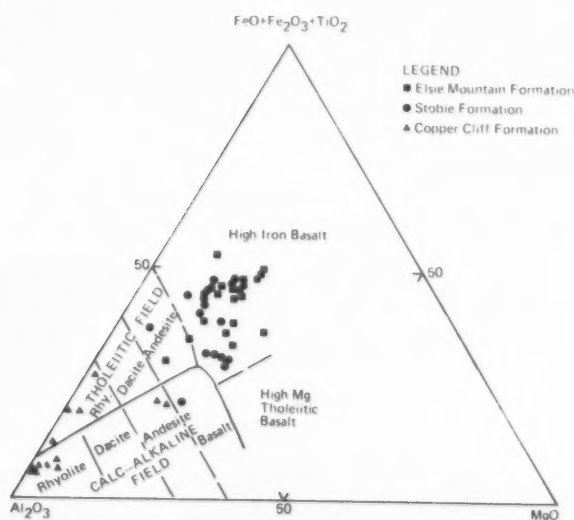


Figure 4.5. Cation plot of Huronian metavolcanic rocks (data from Innes 1977).

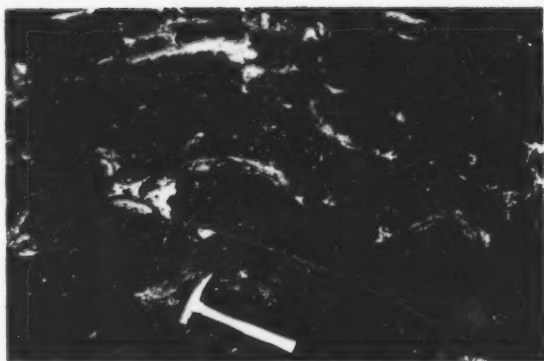


Photo 4.3. Pillowed basalt. Stobie Formation, Falconbridge Township. Quartz filling between individual pillows.

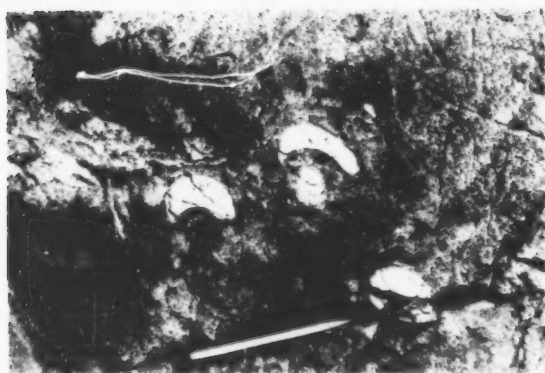


Photo 4.4. "Eye and eyebrow" structures in a dacite flow. Stobie Formation, McKim Township. The structures always assume the same attitude within the flows; the convex side of the eyebrows pointing to the top of the flow. "Eye and eyebrows" consist mainly of quartz, are commonly larger toward the top of the flow and may represent gas bubbles which incorporated small bubbles when they slowly moved upward in a stagnant flow.



Photo 4.5. Planar crossbeds. Mississagi Formation, Garson Township.

(Krogh *et al.*, Chapter 20, this volume). Gibbins *et al.* (1972) also obtained a Rb-Sr isochron age of 1780 Ma



Photo 4.6. Trough crossbeds. Serpent Formation, Street Township.

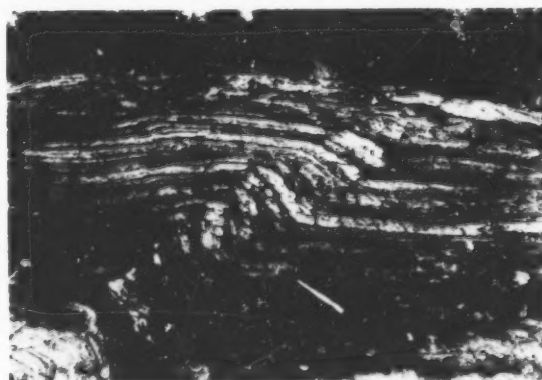


Photo 4.7. Bedded, kink folded arkose. Matinenda Formation, Hyman Township.

for small granitic dikes which crosscut the Murray Pluton, the Huronian metavolcanic rocks, and the norite of the Sudbury Igneous Complex. Krogh *et al.* (Chapter 20, this volume) obtained U-Pb zircon ages of 1865 and 1855 Ma for a granitic dike that intrudes the norite near the Little Stobie Mine.

The contradictory field observations and radiometric age determinations may be explained by as-

TABLE 4.2: GENERALIZED STRATIGRAPHY AND SEDIMENTOLOGY OF THE HURONIAN SUPERGROUP IN THE SUDBURY AREA.SOUTH AND SOUTHWEST OF SUDBURY IGNEOUS COMPLEX (CARD *et al.* 1977)

GROUP	ESTIMATED THICKNESS	STRATIGRAPHY	PRIMARY STRUCTURES
Cobalt	1500–2400 m	Lorrain Formation arkose, feldspathic protoquartzite, wacke, quartz arenite, conglomerate	Festoon crossbedding, graded crossbedding, ripples, ripple-drift cross-lamination
	180–1200 m	Gowganda Formation polymictic paraconglomerate, orthoconglomerate, laminated wacke and mudstone, irregularly laminated wacke and mudstone	Planar crossbedding, festoon crossbedding, parallel lamination, ball and pillow structures, slump folds, ripple-drift cross-lamination, dropstones
Quirke Lake	180–1500 m	Serpent Formation protoquartzite, feldspathic quartzite, arkose, minor siltstone, conglomerate, limestone	Festoon crossbedding, parallel lamination
	150–550 m	Espanola Formation limestone, dolostone, wacke, protoquartzite,	Ball and pillow structures, clastic dikes, slump folds, planar lamination, ripple-drift cross-lamination, desiccation cracks
	60–460 m	Bruce Formation pebbly wacke, conglomerate	Dropstones
Hough Lake	760–3000 m	Mississagi Formation orthoquartzite, arkose, wacke, conglomerate	Festoon crossbedding, planar crossbedding, ripple-drift cross-lamination
	60–600 m	Pecors Formation wacke, quartz feldspar arenite	Bouma layering, ball and pillow structures, clastic dikes
	60–180 m	Ramsey Lake Formation polymictic paraconglomerate, pebbly sandstone	Dropstones
Elliot Lake	1500–1800 m	McKim Formation laminated wacke and mudstone protoquartzite	Bouma layering, clastic dikes, ball and pillow structures, parallel lamination
	180–300 m	Matinenda Formation feldspathic protoquartzite, laminated wacke, oligomictic quartz-pebble conglomerate, polymictic conglomerate	Planar crossbedding
	up to 730 m	Copper Cliff Formation felsic flows, felsic pyroclastic rocks	Crossbedding, graded bedding, amygdules, flows
	up to 1500 m	Stobie Formation mafic flows, pyroclastic rocks, minor wacke	Flow, pillowed flow, amygdules, breccia
	up to 1000 m	Elsie Mountain Formation mafic flows, minor pelitic metasediments, and mafic tuffaceous rocks	Flows, pillowed flows, amygdules, pillow breccia

FALCONBRIDGE AND STREET TOWNSHIPS
(RECONNAISSANCE INVESTIGATIONS BY B. DRESSLER IN 1982)

GROUP	ESTIMATED THICKNESS	STRATIGRAPHY	PRIMARY STRUCTURES
Cobalt	?	Gowganda Formation wacke, conglomerate, arkose	Dropstones, crossbedding in wacke
Quirke Lake	1000–1500 m	Serpent Formation arkose, arkosic wacke, minor conglomerate	Planar crossbedding, festoon crossbedding
	375 m	Espanola Formation wacke, limestone	Parallel lamination, algal mats (?)
	250 m	Bruce Formation conglomerate, pebbly wacke	Dropstones
Hough Lake	1150 m	Mississagi Formation arkose, arkosic wacke, minor conglomerate	Planar crossbedding, festoon crossbedding, ripples, sandwaves
	50–495 m	Ramsey Lake Formation polymictic conglomerate to pebbly wacke	Dropstones
Elliot Lake	0–100 m	McKim Formation laminated mudstone and wacke	Parallel lamination, ripples, ball and pillow structures, Bouma layering
	1000 m	Stobie Formation mafic flows and pyroclastic rocks, minor felsic flows and wackes	Flow, pillowed flows, amygdules, pyroclastic breccias

NORTHERN WANAPITEI LAKE AREA
(DRESSLER 1981, 1982)

GROUP	ESTIMATED THICKNESS	STRATIGRAPHY	PRIMARY STRUCTURES
Cobalt	3300 m	Lorrain Formation arkose, quartz arenite, minor wacke, paraconglomerate	Crossbedding, ripples, lag layers, graded bedding
	950–2700 m	Gowganda Formation massive and laminated wacke; conglomerate (minor just north of Wanapitei Lake, common in lower Gowganda Formation approximately 15 km north of Wanapitei Lake), minor arkose	Parallel lamination, soft sediment deformation, dropstones, clastic dikes
Quirke Lake	0–380 m	Serpent Formation arkose, minor wacke	Crossbedding, graded bedding
	0–250 m	Espanola Formation limestone and wacke	Parallel lamination
	0–> 100 m	Bruce Formation conglomerate and pebbly wacke	Dropstones
Hough Lake	up to 425 m	Mississagi Formation arkose, arkosic wacke, minor conglomerate	Crossbedding

suming granitic intrusions of several ages or by assuming a remelting of pre-Sudbury Igneous Complex granitic rocks by heat emanating from a noritic magma with a crystallization temperature well above the melting point of a granite. Remelting of the Creighton Pluton and small intrusions of the melt into the norite can be observed along the granite's northern contact (Photo 4.8).

The Creighton Pluton rocks are pink or grey and coarse grained, and commonly have a porphyritic texture. Phenocrysts consisting of microcline and sodic plagioclase (Card 1978a) are up to 2.5 cm in size and occur in a medium- to coarse-grained groundmass of quartz, plagioclase, perthitic microcline, and minor biotite (Figure 4.6). Secondary minerals such as chlorite, sericite, and epidote also occur. The Murray and Skead Plutons are medium grained, and are commonly equigranular. Like the Creighton Pluton, these "granites" exhibit a common mineralogy for granitic rocks. The Skead Pluton, lying close to several major faults, has been strongly cataclastically deformed and is stained dark pinkish red by hydrothermal hematite alteration. The "granite" has not been dated radiometrically, and exhibits contradictory contact relationships with rocks of the Huronian Supergroup and the Nipissing gabbros. The classification of the Skead Pluton as being Early Proterozoic in age, therefore, is tentative.

Nipissing Intrusive Rocks

Early Proterozoic gabbro bodies intrude Huronian and older rocks throughout the Southern Province in an area extending from Sault Ste. Marie to Cobalt, Ontario. These rocks are collectively termed Nipissing Diabase, or, in the Sudbury area, Sudbury gabbro. Their Rb/Sr whole rock radiometric ages have been determined at 2150 ± 50 Ma in the Blind River area (Van Schmus 1965) and as 2160 ± 60 Ma in the Gowganda area (Fairbairn *et al.* 1969). Symons (1970)

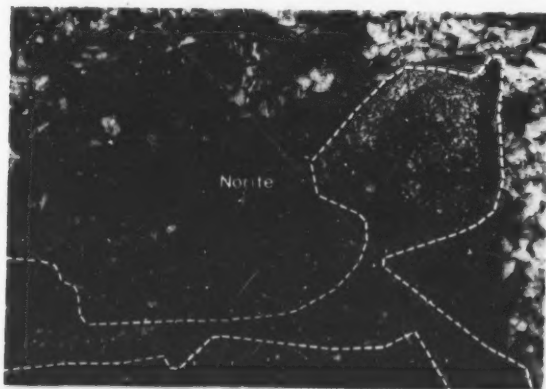


Photo 4.8. Mushroom shaped body of re-melted, contaminated Creighton Granite intruding South Range Sudbury Igneous Complex. Graham Township.

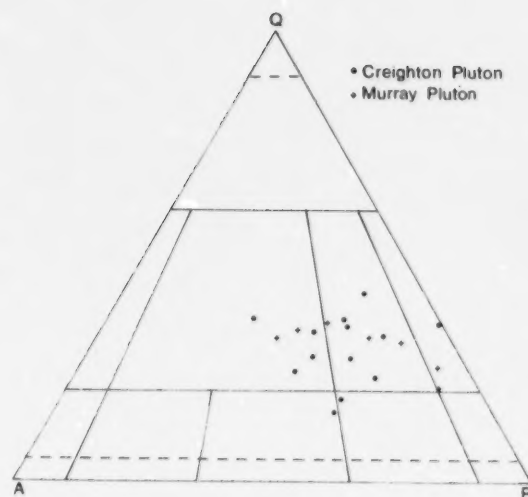


Figure 4.6. Modal composition of Creighton (solid circle) and Murray (+) Plutons. Q—quartz, A—alkali-feldspars, P—plagioclase.

has determined a palaeomagnetic pole position for the Nipissing gabbro at Cobalt of 91.9° E, 19.4° N.

The Nipissing gabbro intrusions were emplaced after early faulting and folding of the Huronian rocks, tectonic events that probably are correlative with the Penokean Orogeny (Church 1968). Regional faults and contacts between rock units acted as channelways for the gabbroic magma to form dikes, sills, and basin and arch structures.

Petrographical and geochemical studies of the Nipissing Intrusive Rocks have been made by Bowen (1910), Coleman (1914), Collins (1917, 1925), Hriskevich (1968), Card (1976), Card and Pattison (1973), Finn (1981), and Dressler (1982), among others.

Petrographically, Nipissing gabbro bodies can be described as hypersthene gabbro, feldspathic pyroxenite, 2-pyroxene quartz gabbro, and hornblende gabbro (Card and Pattison 1973). Minor, more felsic differentiates are granodiorite and granophyre. In the Sudbury area northeast of the Sudbury Igneous Complex, 2-pyroxene quartz gabbro predominates. Granodioritic differentiates are common on the southern shore of Lake Wanapitei (Dressler 1982).

Olivine has not been observed in the Nipissing gabbro of the Sudbury area. Orthopyroxene makes up 1 to 10 modal %, uncommonly as much as 18 modal % of the gabbro in the Lake Wanapitei area (Dressler 1982) and up to 43 % of the gabbro in the southern Sudbury area (Card and Pattison 1973). Clinopyroxene makes up 30 to 46 modal % of the rock (Card and Pattison 1973; Dressler 1982). Zoned plagioclase rim compositions are about An_{45} to An_{55} , and core compositions are about An_{55} to An_{62} (Dressler 1982) in a common 2-pyroxene quartz gabbro. In feldspathic pyroxenite, rim compositions are about An_{65} (Card and

Pattison 1973). Quartz (up to 10 modal %), biotite, titanite, apatite, and opaque minerals are common accessory constituents. Products of metamorphic alterations are amphibole, chlorite, epidote, leucoxene, and carbonate.

In the Sudbury area, the gabbroic rocks were commonly subjected to regional greenschist facies metamorphism. Only south of the Sudbury Igneous Complex were these rocks subjected to greenschist to amphibolite facies metamorphism.

Geochemically, the Nipissing Intrusive Rocks are tholeiitic in composition (Figure 4.7). Thick gabbroic sills are differentiated with granophyric, gabbro-pegmatitic, or granodioritic rocks at their tops. The Lake Wanapitei Nipissing Gabbro Intrusion (Dressler 1982; Finn 1981), at the northeastern shore of Lake Wanapitei, exhibits an initial Mg enrichment differentiation trend at its base.

Base- and precious-metal mineralization is commonly associated with Nipissing Intrusions (Innes and Colvine 1979; Chapter 3, this volume). Card and Pattison (1973) have described regional variations in mineralization. These authors stated that in the Sudbury area, copper-nickel sulphide disseminations and massive pods occur within the gabbroic rocks and in associated quartz-carbonate veins. In the Cobalt area, silver, cobalt, and nickel mineralization occurs in carbonate veins. In the Elliot Lake-Sault Ste. Marie region, quartz-carbonate veins with copper sulphide mineralization are associated with Nipissing gabbro intrusions.

The Sudbury Structure

Lithological units of the Sudbury Structure are listed in geochronological order in Table 4.3. The following

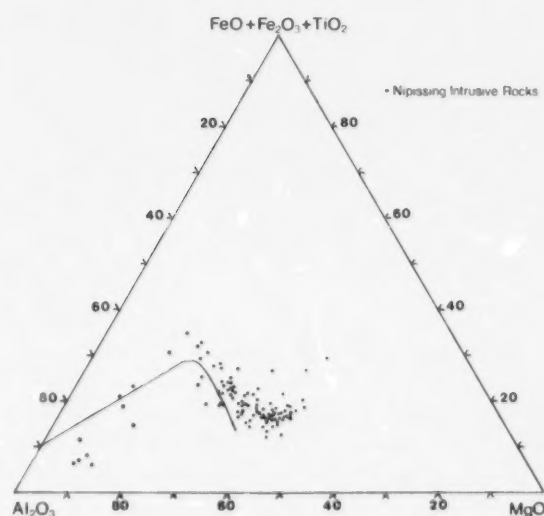


Figure 4.7. Cation plot of Nipissing Intrusive Rocks.

description of these units is very limited; all rock units associated with the Sudbury Structure are dealt with in other chapters of the present volume.

BRECCIAS IN THE FOOTWALL OF THE SUDBURY STRUCTURE

The breccias in the Footwall of the Sudbury Structure, namely the Sudbury Breccia and the Footwall Breccia, are described in detail by Dressler (Chapter 6, this volume), and are not discussed herein.

WHITEWATER GROUP

The Whitewater Group occurs only within the Sudbury Basin. The group comprises 3 formations; the Onaping, Onwatin, and Chelmsford Formations. The group is older than the Sudbury Igneous Complex and gabbroic rocks (map unit 35, Sudbury compilation map, Map 2491, back pocket) that intrude the group in several places at or near the boundary between the Onwatin and Chelmsford Formations. The Onaping Formation is described in detail by Muir and Peredery (Chapter 7, this volume), and the Onwatin and Chelmsford Formations by Rousell (Chapter 8, this volume).

SUDBURY IGNEOUS COMPLEX

Main Mass

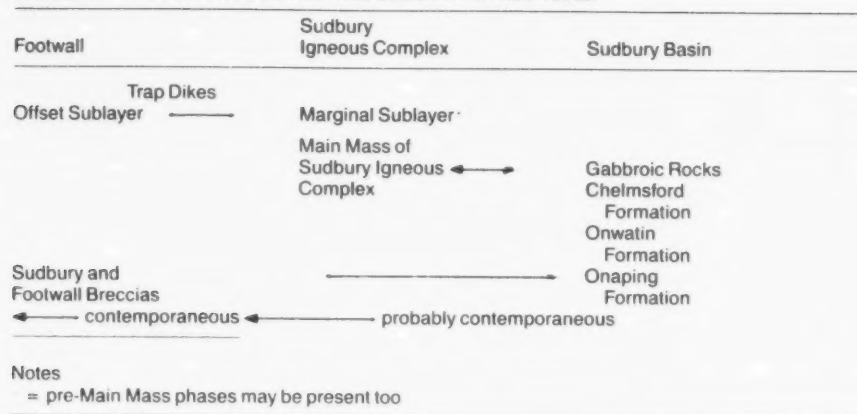
The Main Mass of the Sudbury Igneous Complex is a 1850 Ma old (Krogh *et al.* 1982, Krogh *et al.*, this volume) differentiated intrusion. On the Sudbury compilation map (Map 2491, back pocket), it is divided into 3 phases, termed the Lower, Middle, and Upper Zones. The South Range Lower Zone is made up of norite, and quartz-rich norite, whereas the North Range Lower Zone consists of felsic norite and mafic norite. The quartz gabbro of the Middle Zone corresponds to the "transition zone norite" on older maps on which the Upper Zone of granophyre and plagioclase-rich granophyre appeared as "micropegmatite".

The Sudbury Igneous Complex has an elliptical outline, is approximately 60 km long and 25 km wide, and has the shape of an asymmetric funnel. The southern and eastern limbs of the intrusion dip steeply northward or vertically, the northern limb dips about 30° to 50° south.

Naldrett *et al.* (1970) have described the petrographical and mineralogical variations of rocks encountered in several traverses across the Sudbury Igneous Complex, and discussed the principal differences between the South Range and North Range lithologies (*see also* Naldrett, Chapter 10, this volume).

The North and East Range rocks resemble each other and are different to the South Range rocks. The North and East Range felsic norite (Naldrett *et al.*

TABLE 4.3: GEOCHRONOLOGY OF THE SUDBURY STRUCTURE.



1970) is described as a plagioclase orthocumulate, overlain by the oxide-rich gabbro. This is the quartz gabbro of the Middle Zone, a plagioclase-augite-ulvospinel orthocumulate, which in turn is overlain by the granophyre and plagioclase-rich granophyre of the Upper Zone.

In the South Range Igneous Complex, the "quartz-rich norite" at the base is characterized by an upward decrease in quartz and granophyre content from a combined 22% to just under 10%. The quartz-rich norite is overlain by the "South Range norite", a plagioclase-hypersthene mesocumulate, which in turn is overlain by the "upper gabbro", a rock unit similar to the North Range oxide-rich gabbro. The "upper gabbro" grades upward into the granophyre (Naldrett, Chapter 10, this volume).

Sublayer²

The Sublayer (Igneous Sublayer of Pattison 1979) occurs as lenses and flat sheets along the contact of the Sudbury Igneous Complex norite with the underlying Footwall and Footwall Breccias, and also forms "offsets" intruding into the Footwall rocks and "internal offsets" intruding the Sudbury Igneous Complex norite. The Sublayer consists of an inclusion-bearing gabbroic to quartz dioritic rock. It hosts many of the nickel-copper ore bodies of the Sudbury area. Several intrusive Sublayer phases are recognized.

The oldest phase consists of a fine- to medium-grained, in places, coarse-grained, gabbroic rock that contains mainly ultramafic and mafic plutonic rock fragments and sulphide fragments. The fragments range in size from 1 to 2 cm. to approximately 1 m. and are commonly rounded to spherical (Photo 4.9). Rae

²This short account on the Sublayer is based on the work of the author and some of the observations and interpretations are a matter of controversy amongst Sudbury geologists.



Photo 4.9. Sublayer (oldest phase). Levack Township.

(1975) in a study of the Sublayer from the Strathcona Mine in Levack Township, described fragments of wehrlite, clinopyroxenite, websterite, ilherzolite, dunite, and several other mafic and ultramafic rocks. The matrix contains minor scattered to abundant amounts of nickel and copper sulphide minerals. In several places, for example at a small open pit at the road that leads to the Victoria Mine in Denison Township, the matrix is strongly altered, chloritized, and sheared.

Surface exposures of the younger Sublayer phases are much more common than exposures of the older phase. These consist of medium-grained, gabbroic to quartz dioritic rocks. Fragments are composed of Footwall rocks, mainly mafic metavolcanic and gabbroic rocks. Fragments of the oldest, ultramafic and mafic fragment-rich Sublayer phase, fragments of clastic Huronian metasedimentary rocks, granitic rocks, anorthosite, Footwall Breccia, and Sudbury Igneous Complex norite also occur. Sudbury Breccia fragments are also observed. The fragments are subangular to subrounded (Photo 4.10) in contrast to the rounded to spherical shape of the mafic and ultramafic fragments in the oldest Sublayer phase. These fragments are commonly 1 to 50 cm in size. The arrangement of tabular inclusions of feldspathized laminated metasedimentary rocks (Photo 4.11) and of other similarly shaped fragments indicate flowage parallel to the Sudbury Igneous Complex-Footwall contact. In one place in McKim Township, 2 almost identical phases of the younger Sublayer were recognized.

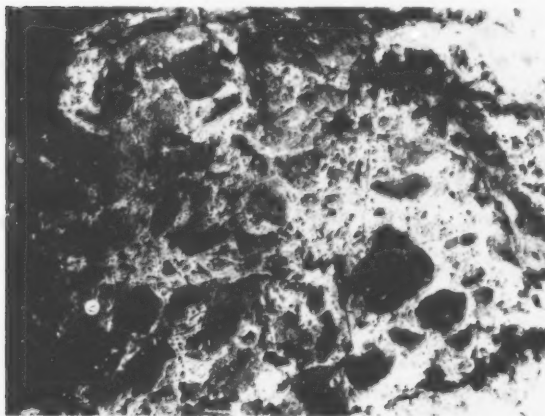


Photo 4.10. Sublayer (younger phase). Whistle Property, Norman Township.



Photo 4.11. Partly disintegrated laminated metasedimentary rock in Sublayer. Snider Township.

The younger phases of the Sublayer post date the norite of the Sudbury Igneous Complex. These phases contain inclusions of norite from the Sudbury Igneous Complex and form "internal offsets" that intrude the norite (see Naldrett *et al.*, Chapter 11, this volume). Along contacts with the norite, inclusions within the Sublayer are aligned by flow parallel to the contact which also suggests a post-norite intrusive relationship. The author did not encounter any field evidence for a pre- or post-norite age of the oldest Sublayer phase described above.

Gabbroic Rocks Within the Sudbury Basin

Several small intrusive bodies of gabbroic rocks occur near the contact of the Chelmsford Formation with the Onwatin Formation. Burrows and Rickaby (1930), who first described the rocks, stated that the dip of the elongate dike-like bodies appears to be toward the centre of the Sudbury Basin, suggesting sill-like intrusions. The rocks post date the Whitewater Group. Their absolute age is unknown.

Burrows and Rickaby (1930) described the rocks as being very highly altered to carbonate and chlorite. A few unaltered specimens examined by the author show the primary mineralogy of augite, hornblende, plagioclase, quartz, and pyrite.

The author studied an occurrence of the gabbroic rocks in northeastern Fairbank Township (easting 474900, northing 5154075). Here, the very northern part of the outcrop consists of an unaltered medium-grained, equigranular gabbroic rock that resembles the North Range felsic norite. One 2 cm-sized inclusion of a strongly altered medium-grained gabbroic rock was observed in this gabbroic rock. In thin section, the felsic norite-like rock is revealed to consist of a brown, primary hornblende, and also small relicts of primary clinopyroxene, quartz, granophyre, and apatite. Plagioclase is completely saussuritized. Actinolite, chlorite, epidote, and leucoxene are alteration products.

The main mass of the outcrop consists of a medium-grained, porphyroblastic, dark greenish grey rock. It is completely altered, consisting of very pale brownish amphibole porphyroblasts set in a fine- to medium-grained dense mass of pale greenish actinolite and very little carbonate and epidote. The rock is cut by pink, medium-grained, hornblende-rich aplite veins. The aplite consists of brown hornblende in a dense mass of completely saussuritized plagioclase, minor actinolite, apatite, and very minor carbonate and quartz.

In Table 4.4, analyses of the above described rocks are presented. The analyses lie in the high magnesium-basaltic komatiite field of a cation plot (Figure 4.8).

TABLE 4.4: CHEMICAL ANALYSES OF GABBROS FROM THE INTERIOR OF THE SUDBURY BASIN AND OF TRAP DIKES.

SAMPLE NUMBER	GABBROS			TRAP DIKES							NORTH RANGE	
	82BOD 7301	82BOD 7303	82BOD 7304	82BOD 3010	82BOD 3309	82BOD 3323	82BOD 1104	82BOD 1112	82BOD 1205	82BOD 1206	80BOD 6902	
SiO ₂	51.1	49.5	51.9	65.0	54.7	53.4	45.8	47.9	47.7	52.8	53.0	
Al ₂ O ₃	14.0	9.16	10.0	15.0	14.1	13.8	12.3	14.2	14.2	12.7	15.10	
Fe ₂ O ₃	2.52	1.78	2.17	1.69	3.12	3.59	4.81	2.88	3.03	4.79	2.06	
FeO	6.72	8.25	7.45	4.35	8.46	9.03	13.5	9.91	9.67	9.51	8.32	
MgO	8.41	14.8	12.2	1.45	4.23	4.64	5.18	6.44	6.83	3.32	4.66	
CaO	11.4	8.88	7.48	3.10	7.48	8.19	10.0	9.25	9.29	7.05	8.36	
Na ₂ O	1.27	1.43	2.18	4.37	2.38	2.15	2.09	2.77	2.47	3.23	2.61	
K ₂ O	0.42	0.97	0.86	2.43	1.48	0.94	0.60	1.30	1.41	1.74	1.51	
TiO ₂	0.75	0.96	0.79	0.95	1.48	1.55	2.04	1.73	1.83	1.87	1.27	
P ₂ O ₅	0.14	0.14	0.18	0.28	0.15	0.16	0.08	0.29	0.32	0.18	0.18	
MnO	0.14	0.16	0.17	0.06	0.18	0.20	0.24	0.17	0.19	0.20	0.18	
CO ₂	0.91	0.33	2.05	0.09	0.17	0.07	0.42	0.24	0.27	0.35	0.06	
S	0.19	0.14	0.05	0.01	0.06	0.12	0.17	0.10	0.09	0.06	0.13	
H ₂ O ⁺	2.08	2.36	2.34	0.78	0.73	0.84	1.14	1.30	1.28	0.77	1.63	
H ₂ O ⁻	0.14	0.10	0.18	0.0	0.07	0.07	0.04	0.03	0.03	0.09	0.22	
LOI	2.9	2.8	3.5	0.3	0.6	0.5	0.9	1.4	1.3	0.8	1.40	
Total	100.2	99.0	100.0	99.6	98.8	98.7	98.4	98.5	98.6	98.7	99.29	

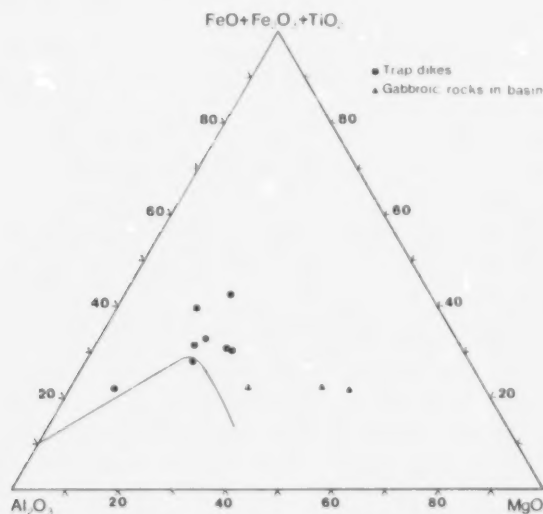


Figure 4.8. Cation plot of gabbroic rocks (solid triangles) from inside the Sudbury Basin and of trap dikes (solid circles).

Trap Dikes

Several post-norite diabase dikes, locally known as "trap" dikes, occur within and just south of the South Range of the Sudbury Igneous Complex. In the North Range, only 1 trap dike is known to occur, that is the one near the Fraser Mine in Levack Township.

The rocks are possibly related to the Sudbury Igneous Complex and are younger than the Main Mass of the Complex. The trap dikes are cut by Middle Proterozoic olivine diabase dikes. Analyses of the fine-grained, dark grey to black uraltic diabases lie in the iron tholeiite field of the cation plot of Figure 4.8. Chemical analyses are listed in Table 4.4.

Grenville Province³

EARLY AND MIDDLE PROTEROZOIC

The northwestern boundary of the Grenville Province is a tectonic zone up to 30 km wide. This zone is characterized by a northeasterly-cataclastic foliation and a southeasterly-plunging rodding lineation (Lumbers 1975). The northern and southern boundaries of the zone are gradational and the only mappable boundary between the Southern Province and the Grenville Province is the Grenville Front Boundary Fault. It separates high metamorphic grade, gneissic rocks of the Grenville Province from low metamorphic grade, cataclastic rocks of the Southern Province, and is a zone of extreme cataclasis and mylonitization up to 30 m wide. At the Boundary Fault, lineations and dips of the cataclastic foliation steepen and, therefore, the Fault possibly dips subvertically. Present geological data suggest that the strike-slip component along the Fault may be minor, and Lumbers (1975) constructed a model to show that the dip-slip component may also be minor.

Rocks of the Grenville Province underlie the southeastern part of the Sudbury compilation map area southeast of the Grenville Front Boundary Fault. The most abundant rocks here are metasediments, these are mainly siliceous arenites and siltstones. Probably, these rocks represent deep water facies equivalents of Huronian sedimentary rocks of the Southern Province northwest of the Boundary Fault (Lumbers 1975). The Grenville sedimentary gneisses commonly were less

³For a detailed account of the Grenville Province part of the compilation map area, the reader is referred to Lumbers (1975).

mature than their equivalents in the Southern Province. Mature shallow water facies rocks also occur, however, and locally are abundant. Minor marble and calc-silicate gneisses in places are interlayered with the clastic metasedimentary rocks (Lumbers 1975).

The Grenville sedimentary gneisses comprise biotite gneiss, feldspathic gneiss, muscovite gneiss, and hornblende gneiss, and are migmatitic in many places.

Granitic plutons form a 105 km long elongate mass, the Killarney Batholith, and lie along the north-western margin of the Grenville Province. These plutons range in age from about 1590 Ma to 1700 Ma (Davis *et al.* 1970). In the Sudbury compilation map area, the Chief Lake Batholith forms part of the Killarney Batholith and was previously mapped as feldspathized quartzite (Phemister 1960). Subsequent work by Lumbers (1975) and others, however, indicates an intrusive origin for these rocks.

Metamorphosed mafic intrusive rocks form dikes, stocks, and small plutons within the metasedimentary rocks. Most of these Early Proterozoic mafic rocks are within the Grenville Front Tectonic Zone, and are most likely metamorphic equivalents of the Nipissing gabbro bodies in the Southern Province (Lumbers 1975).

Gneissic pegmatite dikes are locally present and cut across the metasedimentary rocks and some older mafic intrusive rocks. Gneissic to rarely massive anorthosite to anorthositic gabbro occur in Awrey, Dryden, and Cleland Townships. Monzonitic and granitic rocks are associated with the anorthosite. The anorthosite suite rocks are thought to be younger than the Middle Precambrian granitic rocks. Lumbers (1975) stated that the rocks may range in age from about 1500 Ma to somewhat less than 1200 Ma.

Late mafic intrusive rocks form several small bodies consisting of cataclastic, recrystallized diabase. Most of the bodies are elliptical to circular in plan, and in general are only up to approximately 100 m across. The only larger stock of gabbro, diorite, and minor ultramafic rocks, the Wanapitei Complex (Lumbers 1975), is located southwest of the village of Wanapitei. The stock is cut by numerous dikes of relatively quartz-rich trondhjemite, granodiorite, and associated contaminated felsic rocks. The complex is younger than the anorthosites because the gabbroic rocks of the complex intrude the anorthosite suite rocks along its southwestern flank (Lumbers 1975).

Late granite pegmatite dikes occur in all rocks of the Grenville Province except the post metamorphic mafic intrusions. These dikes were emplaced after the culmination of the Grenville Orogeny and are approximately 1100 to 900 Ma old (Shillibeer and Cumming 1956). The pegmatites within the Grenville Front Tectonic Zone are generally zoned with a quartz-rich

centre. These pegmatites are hematitized, and are somewhat radioactive due to the presence of allanite and minor amounts of other radioactive minerals. The pegmatites are unzoned farther away from the Grenville Front Tectonic Zone, and are low in radioactivity and consist of the common pegmatite minerals such as quartz, alkalic feldspar, and minor micas. The pegmatites in the Grenville Front Tectonic Zone, in addition to these minerals, contain minor amphibole, garnet, magnetite, and specularite, minerals that are found very sparingly in the pegmatites away from the Grenville Front Tectonic Zone.

Following the Grenville Orogeny, a few mafic to ultramafic stocks were emplaced in the Grenville Province by gneisses. Within the Sudbury compilation map area (Map 2491, back pocket) itself, only 1 small ultramafic body occurs. It lies in southwestern Cleland Township and consists of partly serpentinized peridotite with occasional rare plagioclase. According to Lumbers (1975), the Cleland Township, and other ultramafic bodies in adjacent townships nearby, are either within or near the southeastern margin of the Grenville Front Tectonic Zone, and reflect late tectonic activity associated with the Zone.

Southern, Superior, and Grenville Provinces

MIDDLE PROTEROZOIC

Mafic Intrusions

DIABASE

Two types of Middle Proterozoic diabase dikes are present in the Sudbury compilation map area: olivine diabase and diabase that contain only traces or no olivine. The olivine diabase dikes were given the term "Sudbury Swarm" by Fahrig and Jones (1969).

Radiometric K-Ar and Rb-Sr age determinations by Van Schmus (1965) and by Fahrig and Wanless (1963) show that most of the olivine diabase dikes of the Sudbury Swarm are approximately 1250 ± 50 Ma old. More recently, Gates and Hurley (1973) obtained a Rb-Sr isochron age of 1460 ± 130 Ma on Sudbury dikes in the Sudbury area. Fahrig and Wanless (1963) reported K-Ar whole rock ages of 431 ± 80 and 416 ± 76 Ma from dikes that extend across the Grenville Front Tectonic Zone near Killarney southwest of Sudbury. Grant *et al.* (1962) provided geomagnetic evidence that one Southern Province olivine diabase dike terminates at the Grenville Front Boundary Fault. All olivine diabase dikes in the Sudbury compilation map area also do not appear to cross into the Grenville Province. In the Tomiko area, however, Lumbers

(1971a, 1971b) showed that some olivine diabase dikes do in fact intrude rocks of the Grenville Province.

The radiometric ages, the widespread occurrence, and the rather constant geographic orientation of most dikes imply that the intrusion of the dikes occurred under regional tensional stress over a long period of time. This tensional stress appears to have been a large scale tectonic feature because the Sudbury Swarm dikes are similar in trend, paleomagnetic properties, and age to the Mackenzie Swarm in the northern Canadian Shield (Fahrig and Jones 1969).

The olivine diabase dikes are common throughout the Superior and Southern Province rocks within the Sudbury area. The dikes are post-tectonic, unmetamorphosed, and commonly trend northwest. The dikes are from 10 cm to about 250 m wide. Some can be traced for distances of 80 km at least. They are dark grey, brown weathering, commonly medium grained, and in places are very coarse grained and plagioclase porphyritic. Plagioclase ($An\ 65 \pm 5$), augite, olivine (Fo 55-70; Fa 45-30), and biotite are the main rock-forming minerals.

Chemical and mineralogical characteristics (Figure 4.9) of the olivine diabases indicate that they were derived from a common magma. Their chemical composition and low initial Sr 87/Sr 86 ratio of 0.703 (Gates 1971) indicate an homogeneous mantle source origin.

Little is known about the post-metamorphic diabase dikes that contain little or no olivine. These dikes

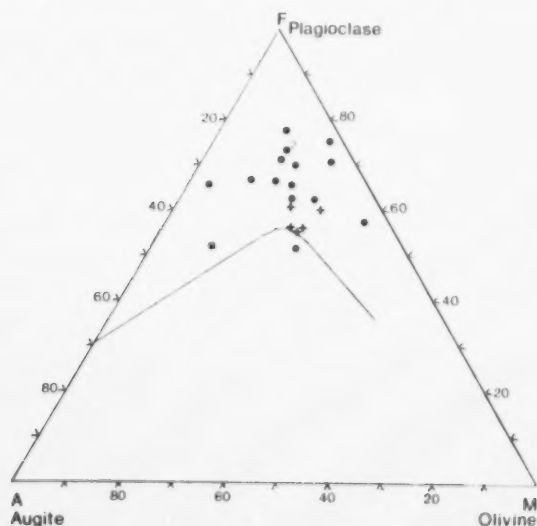


Figure 4.9. Chemical (+) ($A = Na_2O + K_2O$; $F = FeO + 0.8996 Fe_2O_3$; $M = MgO$), and mineralogical (solid circles) characteristics of olivine diabase, Sudbury area. Data from published Ontario Geological Survey reports.

are very scarce and only 1 occurrence is known in the Sudbury compilation map area. It lies in Dryden Township, and is exposed over a length of little more than 1 km. Like most of the olivine free post-metamorphic diabase dikes, it strikes westerly, as do the "trap" dikes on the opposite side of the Grenville Front Tectonic Zone. This suggests a common origin and age.

Lumbers (1975) described the olivine-free dikes in the Burwash area east of Sudbury as being mainly slightly altered. In a few places, however, these dikes consist of extensively saussuritized diabase.

Metamorphism

The metamorphic geology of the Sudbury area reflects several metamorphic episodes during Archean and Proterozoic times.

SUPERIOR PROVINCE

North and east of the Sudbury Igneous Complex in the terrain underlain by Archean rocks, 2 distinct and different metamorphic regimes can be recognized. The first is documented by granulite and amphibolite facies gneisses that occur mainly in Levack and neighbouring townships. The second is characterized by greenschist and amphibolite facies metasedimentary and metavolcanic rocks.

The granulite and amphibolite facies gneisses north of the Sudbury Igneous Complex are commonly known as the "Levack Gneiss Complex" (Langford 1960) and are characterized by the mineral assemblages listed in Table 4.5.

The occurrence of high rank metamorphism so close to the Sudbury Igneous Complex is intriguing. It may be explained by assuming either a pre-Sudbury event metamorphic high at the present site of the Sudbury Structure; or, by assuming an uplifting or up-thrusting of deeper crustal material during the Sudbury crater forming event.

TABLE 4.5: PRE-SUDBURY IGNEOUS COMPLEX METAMORPHIC AND RETROGRADE MINERAL ASSEMBLAGES OBSERVED IN THE "LEVACK GNEISS COMPLEX" OF LEVACK TOWNSHIP.

cpx-(opx)-pl-qtz	0-1, rarely 1.5 km away from the Sudbury Igneous Complex, minor retrograde minerals; 13 thin sections studied
cpx-opx-pl-bi-qtz	
cpx-pl-bi and/or hbl-qtz	
cpx-pl-bi-garnet-qtz	
cpx-pl-qtz	
bi-pl-qtz	Northern and north-central Levack Township; 7 thin sections studied (amphibolite facies and retrograde metamorphism)
pl-chlorite-qtz	
pl-bi-actinolite-qtz	

The greenschist to amphibolite facies mineral assemblages of the metasedimentary and metavolcanic rocks of the Benny Belt were studied in detail by Card and Innes (1981). Meyn (1970) listed modal analyses of greenschist and amphibolite facies metavolcanic rocks from Hutton and Parkin Townships. Card and Innes (1981) presented a metamorphic map of the Benny area showing that most of the Benny Belt is underlain by amphibolite facies rocks. The eastern part of the Benny Belt in Moncrieff, Hess, and Munster Townships is characterized by greenschist facies rocks from north of Bannerman Lake to somewhat north of the northern Moncrieff Township boundary, and mainly amphibolite facies rocks in Hess Township. Table 4.6 lists mineral assemblages observed by Card and Innes (1981).

TABLE 4.6: METAMORPHIC MINERAL ASSEMBLAGES OF METASEDIMENTARY AND METAVOLCANIC ROCKS, BENNY AREA (after Card and Innes 1981).

AMPHIBOLITE FACIES

Mafic and intermediate metavolcanic rocks

hbl-pl

hbl-pl-epid.-qtz

hbl-pl-bi-garnet-epid.-qtz

Felsic metavolcanic rocks

pl-Kspar-qtz ($\pm$ bi, hbl, epid)

Pelitic metasedimentary rocks

pl-hbl-bi-qtz

GREENSCHIST FACIES

Mafic and intermediate metavolcanic rocks

chl-musc.-pl-epid.-qtz

chl-bi-musc.-pl-epid.-qtz

chl-bi-actin.-pl-epid.-qtz

Felsic metavolcanic rocks, epidotized

musc-pl-Kspar-qtz

chl-musc-feldspars-qtz

bi-musc-feldspars-qtz

Pelitic metasedimentary rocks, epidotized

musc-chl-pl-qtz

bi-musc-chl-pl-epid.-qtz

SOUTHERN PROVINCE

The Early Proterozoic supracrustal and intrusive rocks of the Sudbury compilation map area were deformed and metamorphosed during several metamorphic events. Card *et al.* (1973) and Dressler (1982) presented evidence suggesting large scale pre-Gowganda folding and faulting of the pre-Cobalt Group Huronian sequence in the Cobalt Embayment. Card (1978b) listed evidence for a pre-Nipissing deformation and a later low to middle rank grade metamorphism affecting rocks of the Huronian Supergroup which probably occurred during the emplacement of the Murray and Creighton Plutons. Stockwell (1982, Figure 11) listed a K-Ar age of approximately 2080 Ma for a Huronian rock in the Murray metamorphic node and Stockwell (1982, Figure 10a) presented several K-Ar and Rb-Sr ages that are all closely correlative with the age of Nipissing intrusions.

Most metamorphosed rocks of the Huronian Supergroup and other rocks of the Southern Province yield K-Ar and Rb-Sr mineral and whole rock isochron ages ranging from about 1600 to 1900 Ma. Many of the radiometric ages listed by Stockwell (1982, Figure 10b) cluster around approximately 1700 to 1800 Ma and around 1900 Ma. The first cluster of ages characterizes the Hudsonian Orogeny (Stockwell 1982, Table 3), and the second, the Penokean Orogeny. Because of the rather wide spread of ages, Stockwell (1982, p.53) considered the Penokean Orogeny to be equivalent to an early phase of the Hudsonian Orogeny.

Card (1978b) has published a large scale metamorphic map of the Southern Province showing amphibolite facies rocks in a zone extending from Cutler, 130 km southwest of Sudbury, to Falconbridge Township. This zone is up to 12 km wide and is bounded to the south by low to upper greenschist facies metamorphic rocks that extend to the Grenville Front Tectonic Zone. To the north, it is bounded by low to middle greenschist facies rocks. The northern half of the Sudbury Basin and the North Range Sudbury Igneous Complex is of subgreenschist facies rank.

Card (1978b) listed subgreenschist to amphibolite facies mineral assemblages obtained from the rocks of the Southern Province, including the Sudbury compilation map area. The assemblages range from quartz-kaolinite in the subgreenschist facies rocks, to staurolite and/or andalusite-garnet-biotite-plagioclase and garnet-muscovite-biotite-plagioclase in the amphibolite facies rocks. Staurolites in metapelites (Photo 4.12) in places are up to 25 cm in length. East-northeast of the Creighton Mine, a zone of Huronian metasedimentary rocks has been anatectically remobilized, and shows *lit-par-lit* and pygmatic granitic mobilizes (Photo 4.13). This migmatization probably was caused by the intrusion of the Creighton Pluton. Amphibolite facies mafic metavolcanic rocks may be very coarse grained, and gabbro-like.

GRENVILLE PROVINCE

It is beyond the scope of this summary report to describe in detail the metamorphic history and mineral assemblages of the rocks of the Grenville Province. The following account is based solely on the work of Lumbers (1975).

The Grenville Province is characterized by a complicated history of metamorphism, deformation, and plutonism. In the Middle Proterozoic, after the emplacement of the major plutons, all the rocks of the Grenville Province were subjected to high rank regional metamorphism that culminated between approximately 1400 and 1200 Ma ago. In the waning stages of this metamorphic event, granite pegmatites were emplaced approximately 1100 to 1000 Ma ago.

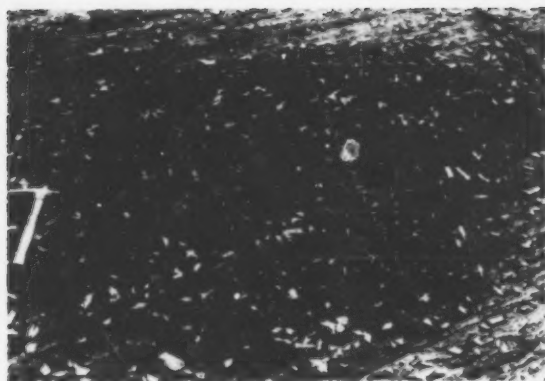


Photo 4.12. Staurolites in metapelite of the Huronian Supergroup just west of Frood Mine, McKim Township.



Photo 4.13. Ptygmatic mobilizate in Huronian Supergroup metasediment, 3 km north of Meatbird Lake, 2.5 km east-northeast of Creighton Mine.

An older Early Proterozoic metamorphism that had affected the Grenville metasedimentary rocks of the Sudbury compilation map area is indicated by syn- or pre-tectonic, intensely-deformed Early Proterozoic granites within the sedimentary gneisses, and also by the presence of Early Proterozoic gneissic pegmatites that occur mainly within the Grenville Front Tectonic Zone.

Mineral assemblages of the sedimentary gneisses reflect the Middle Proterozoic metamorphism only, and are typical of the kyanite-almandine-muscovite subfacies of the amphibolite facies. Most gneisses contain only plagioclase, quartz, biotite, hornblende, and garnet; an assemblage also compatible with the lower metamorphic staurolite-almandine subfacies. Staurolite has not been observed by Lumbers (1975), whereas kyanite is found in a few places, suggesting that probably all the metasedimentary rocks had been subjected to high rank metamorphism typified by the kyanite-bearing subfacies.

SHOCK-METAMORPHIC AND CONTACT-METAMORPHIC FEATURES RELATED TO THE SUDBURY STRUCTURE

Shatter cones, the macroscopic deformational features related to high pressure shock waves, occur all around the Sudbury Igneous Complex, and are most abundant and best developed in fine- to medium-grained arkoses and wackes of the Huronian Supergroup (Dietz 1964; Dietz and Butler 1964; French 1972; and Dressler, Chapter 6, this volume). These features occur also in the Archean Footwall rocks north of the Sudbury Igneous Complex, and are absent in rocks of the Sudbury Igneous Complex and the Whitewater Group.

Microscopic shock-metamorphic deformational features occur in the Footwall rocks around the Sudbury Igneous Complex and in rock and mineral fragments of the Onaping Formation (French 1972; Peredery 1972b; Dressler, Chapter 6, this volume; Muir and Peredery, Chapter 7, this volume). Shock-metamorphic features observed in Footwall rocks are planar features in quartz and feldspar and kink bands in micas. There is a distinct zoning of diaplectic deformation within the Footwall rocks (Dressler, Chapter 6, this volume), indicating a concentric decrease of shock-metamorphic pressure away from the Sudbury Igneous Complex. Diaplectic features near the Sudbury Igneous Complex in the North Range Footwall rock, in all of the South Range Footwall rocks, in inclusions of the Sublayer and Footwall Breccias, and also in many inclusions in the Onaping Formation have been completely or partly obliterated by recrystallization due to regional metamorphism, or contact-metamorphic effects related to the Sudbury Igneous Complex.

Contact-metamorphic rocks around the Sudbury Igneous Complex are characterized by stubby, decussate plagioclase. The contact-metamorphic zone so defined by this is up to about 1.3 km wide in the North Range Footwall rocks (see Dressler, this volume). Near the North Range norite, pyroxene-hornfels-facies mineral assemblages grade northward into a hornblende-hornfels-facies assemblage and farther into a zone where only plagioclase and quartz appear to be recrystallized. In the South Range Footwall rocks, Hudsonian metamorphism that post-dated the Sudbury Igneous Complex destroyed almost all contact- and shock-metamorphic mineral assemblages.

THE WANAPITEI LAKE CRATER

Dence and Popelar (1972) presented topographic, geophysical, and petrographical evidence for a meteorite impact origin of the Wanapitei Lake Structure. The

topographic indications of this are the approximately circular shape of the lake and the predominantly concentric pattern of streams and lakes within 5 km of Wanapitei Lake. This concentric pattern is substantiated by structural measurements around the lake (Dressler 1982). Geophysical evidence is a local, almost circular gravity depression over the circular part of Wanapitei Lake with a horizontal gradient of more than 4 mgal/km outward from the centre of the depression. This, according to Dence and Popelar (1972) suggests a superficial mass deficiency having a circular plan. Petrographic evidence comes from suevite pebbles and boulders scoured from the lake during the last period of glaciation. The suevite of the type location, the Nördlinger Ries in Germany, is an impact breccia containing fragments of shock-metamorphosed rocks and diaplectic glass set in a matrix of fine-grained mineral, rock, and glass fragments. The Wanapitei Lake suevite is identical to the Ries suevite in its macroscopic and microscopic characteristics. Like the Ries suevite, it contains coesite (Dence *et al.* 1974). Further petrographic evidence for a meteorite impact origin of the Wanapitei Lake Structure comes from shatter cones found on the shore, or on the islands of Wanapitei Lake (Dressler 1982), and from shock-metamorphic planar features in quartz observed at several locations. These microscopic features, however, were observed only in rocks on the western shore of Wanapitei Lake and on an island close to this shore and, therefore, are possibly related to the Sudbury Structure located about 5 km to the west. Winzer *et al.* (1976) obtained a K-Ar age of 37 Ma from diaplectic glasses from Wanapitei suevites. This young age is close to a 34 Ma meteorite impact suggested by Ganapathy (1982) to have occurred on the earth approximately at this time.

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CHAPTER 5

Structural Geology of the Sudbury Basin

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ABSTRACT

The Sudbury Basin was deformed by the Penokean Orogeny approximately 1750 Ma ago. The maximum principal stress was directed toward the northwest and the deformation intensity decreased in that direction. In the South and East Ranges, the rocks of the Onaping Formation and the granophyre behaved in a ductile manner, were shortened, tectonically thickened, and developed a foliation and lineation. Isoclinal similar

folds formed at the top and bottom of the Onaping Formation. The brittle norite yielded by reverse faulting. Toward the later stages of deformation, the South Range was rotated in a reverse sense. This led to an overturning to the northwest of the isoclinal folds and the contact between the Onaping Formation and the Onwatin Formation. Farther to the northwest, the rocks of the Onwatin Formation developed a slaty cleavage. In the central part of the basin, the rocks of the Chelmsford Formation formed relatively open,

upright, concentric folds. The pelitic rocks of the formation developed an axial-plane cleavage, while in the greywacke layers, a fracture cleavage formed in the outer arc of the hinges of the folds. In the North Range, the only vestige of the deformation is a local and weak foliation.

Kink bands in the Onaping Formation have horizontal hinges and a reverse sense of external rotation and represent late orogenic features. Steeply dipping north-northwest-striking extension joints formed as a result of post-orogenic uplift and extension of the basin along a west-northwest east-southeast axis. An episode of regional crustal extension led to the formation of west-northwest extension joints and diabase dikes (1250 Ma). This was followed by a reactivation of the faults of the Onaping set and the development of north-northwest trending shear joints parallel to the faults. Finally, the Wanapitei meteorite impact (37 Ma) deflected the East Range so to become convex to the southwest.

The Sudbury Basin was certainly less elliptical in the past, than its present form in plan view, but it is unlikely that it was ever circular. The basin, prior to deformation, may have been approximately 62 km long and 41 km wide. The ratio long axis/short axis of the restored basin is 1.5 compared to a ratio of 2.2 for the present basin.

INTRODUCTION

The Sudbury Basin was effected by an orogenic event that took place 1750 ± 50 Ma ago. Deformation apparently began relatively soon after the formation of the basin (1849 Ma). The basin was shortened by a push toward the northwest, and this produced a number of structural elements including foliation, lineation, cleavages, folds, faults, and joints. The deformation intensity decreased toward the northwest as is indicated by a change in the style and degree of development of certain elements. Kink bands developed late in the orogenic period and 2 post-orogenic episodes of crustal extension produced joints. This was followed by faulting and the formation of joints in the North Range. Finally, the arcuate-shape of the East Range may have been produced by the Wanapitei Event (37 Ma). An outline of the tectonic history of the Sudbury Basin is given in Table 5.1. A generalized representation of the structural elements of the basin, except joints, is shown on the map of Figure 5.1, plots of kink bands are shown in Figure 5.2, and the orientation of the major joint sets are indicated in Figure 5.3.

In the following account, the structural elements are first described. This is followed by an interpretation of the tectonic history of the basin. Finally, various attempts to reconstruct the original shape of the basin are discussed.

FOLIATION AND LINEATION

A tectonic foliation and lineation (Photo 5.1) occur in the Onaping Formation of the South and East Ranges (Brocoum and Dalziel 1974; Rousell 1975; Everitt 1979). These structures gradually fade out into the North Range, although a weak foliation occurs in the central part of the North Range. The foliation is due to the dimensional preferred orientation of elongated rock and mineral fragments, platy minerals such as biotite and chlorite, and prismatic tremolite-actinolite. The fragments are tectonically elongated such that the long and intermediate axes lie in the foliation plane and with the short axes perpendicular to this plane. The long axes define a lineation that is oriented down the dip of the foliation plane (pitch is 90°) in the central part of the South Range, and has a southwesterly pitch, as little as 39° , at either end of the South Range. These structures also occur in the granophyre and locally in the norite of the South Range. In the South Range, the foliation generally strikes northeasterly. At the southwestern end of this Range, the foliation, however, wraps around a fault block of the Sudbury Igneous Complex. There are bulges at either end of the East Range and the foliation strikes parallel to the axes of the bulges. The foliation in the Onaping Formation dips a little or at 30° , and as much as 85° , and invariably to the southeast, south, or southwest.

In almost all quartzite breccia fragments in the Onaping Formation of the South and East Ranges, the quartz is completely recrystallized and optic axes lack



Photo 5.1. Tectonically elongated quartzite fragments and foliation in the Onaping Formation. Northeastern end of the South Range and south of the Canadian Armed Forces radar station.

TABLE 5.1: OUTLINE OF THE TECTONIC HISTORY OF THE SUDBURY BASIN.

EVENT AND AGE (Ma)	REMARKS
Wanapitei Event (37)	Deformation of the East Range Faults of the Onaping Set and NNW joints
Diabase dikes (1250)	WNW extension joints
Post orogenic	NNW extension joints
Late orogenic	Kink bands, annealing recrystallization
Penokean Orogeny (1750 ± 50)	Basin shortening; foliation, lineation, cleavage, folds, longitudinal faults, and diagonal faults Three joint sets in Sudbury Igneous Complex Gabbro sills
Sudbury Event (1849)	Whitewater Group, Sudbury Igneous Complex

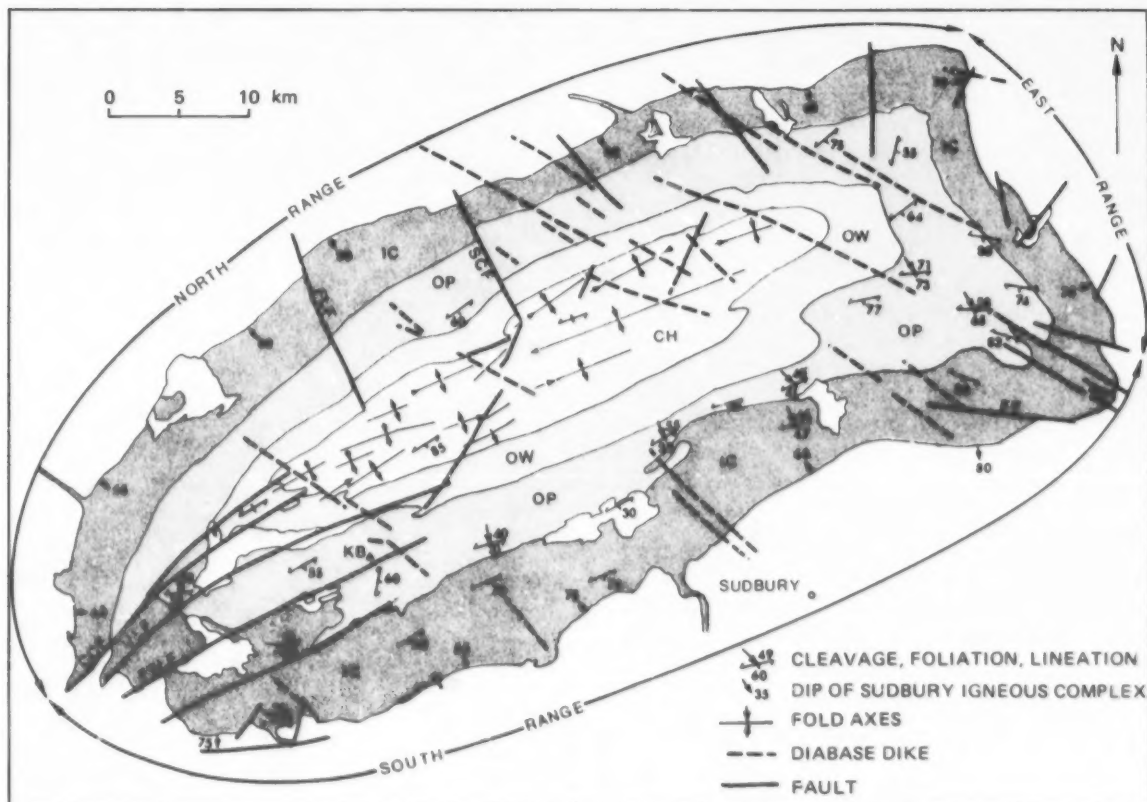


Figure 5.1. Generalized map of the structural elements of the basin. IC—Sudbury Igneous Complex, OP—Onaping Formation, OW—Onwatn Formation, CH—Chelmsford Formation, KB—Kink Bands, CCF—Cameron Creek Fault, VLF—Vermilion Lake Fault, FBLF—Fairbank Lake Fault, FLF—Fecunis Lake Fault, SCF—Sandcherry Creek Fault, and FF—Falconbridge Fault.

a consistent preferred orientation (Rousell 1976). This suggests an episode of post-tectonic annealing recrystallization. The quartzite breccia at the eastern end of the South Range apparently escaped annealing recrystallization. There, the quartz occurs as elongate ribbons displaying extreme undulatory extinction and has small recrystallized grains at their boundaries. The ribbons impart a foliated character to the rock. Stereographic plots indicate that the optic axes of the ribbon and recrystallized quartz lie on small circle girdles

with the girdle axes perpendicular to the foliation plane. The texture and the orientation of the optic axes in the quartzite breccias are similar to those in quartzites experimentally deformed by Tullis *et al.* (1973) at temperatures of 700°C and strain rates of $10^{-7}/\text{s}$. Quartz grains are flattened to form a foliation and the girdle axes and maximum principal stress are normal to the foliation. The ribbon quartz in the Onaping breccias represent a mylonitic texture produced by intragranular plastic deformation.

Burrows and Rickaby (1930) regarded the foliation as a product of shearing and referred to the texture as cataclastic. Thomson (1957) also considered the rocks of the South Range to be "well-sheared"; the shearing was ascribed to overthrust faulting and folding.

Rousell (1975) argued that the foliation planes in the Onaping Formation cannot be shear planes because: the long axes of glass fragments lie in the foliation plane even in weakly deformed rocks; and the fragments are not cut and offset by the foliation planes. Rousell (1975) suggested that the rocks behaved in a ductile manner and that the foliation and lineation were produced by a constriction-type pure strain ($a > k > 1$, Flinn 1962). Considerable shortening took place normal to the foliation, there was moderate shortening normal to the lineation and parallel to the foliation, and extreme extension occurred parallel to the lineation. Slickensides that locally occur in the foliation plane are ascribed to slippage that took place after the formation of the foliation.

The schistosity (S) that initially develops in ductile shear zones is parallel to the XY plane of the finite strain ellipsoid (Ramsay and Graham 1970). The schistosity intersects the shear zone boundary at 45° . As deformation proceeds, the schistosity in the central part of the zone rotates so that the angle with the boundary decreases and may eventually approach 0° . As strain becomes large, discrete slip planes (C) may develop. These are oriented parallel to the shear zone boundaries, display slickensides, and may eventually destroy the schistosity (Berthé *et al.* 1979).

If the foliation in the Onaping Formation represents a schistosity (S) that developed in a reverse ductile shear zone, then the foliation should dip steeply to the northeast (where it dies out) and decrease in dip to the southeast. Such a pattern is not clearly evident on existing maps (Brocoum and Dalziel 1974; Rousell 1975; Everitt 1979). There are microfabric criteria that can be used to deduce the sense of movement in shear zones (Simpson and Schmid 1983), but none have been reported from the Onaping Formation.

In conclusion, the foliation in the South and East Ranges could have formed parallel to the XY plane of the finite strain ellipsoid, or it could be due to a pure strain. Available evidence tends to favour the latter origin.

SLATY AND FRACTURE CLEAVAGE

The Onwatin Formation overlies the Onaping Formation and consists of argillite and siltstone. The formation is characterized by a slaty cleavage that dips

steeply and strikes in a northeasterly direction. The cleavage does not displace the bedding.

The Chelmsford Formation overlies the Onwatin Formation and is composed largely of greywacke layers, commonly graded, having an average thickness of approximately 1 m. The greywacke layers are generally separated by layers of argillite and siltstone approximately 15 cm thick. The formation is folded. The greywacke layers display a fracture cleavage (Photo 5.2) that is normal to the bedding and strikes parallel to the axial planes of the folds. The cleavage is fan-like, opening upward in anticlines and downward in synclines. In graded beds, the cleavage is arcuate; it is normal to the bedding at the base, curving toward parallelism with the axial plane at the top. The argillite and siltstone layers have a slaty cleavage that is more closely spaced and regular than the fracture cleavage. Layer-parallel slippage, at the contact between greywacke and argillite-siltstone, caused a slight rotation of the cleavage. The cleavage, in passing from argillite-siltstone to greywacke, is refracted toward the normal to bedding planes.

Brocoum and Dalziel (1974) suggested that the axis of maximum shortening strain is normal to the cleavage in the Onwatin and Chelmsford Formations.



Photo 5.2. Fracture cleavage in the Chelmsford Formation. Abandoned section of Highway 144 north of railroad overpass.

The refraction of the cleavage in the Chelmsford Formation indicates this is an oversimplification. According to Rousell (1975), the fracture cleavage formed in the greywacke layers at an early stage of the folding and the cleavage rotated as folding proceeded. The more ductile argillite-siltstone layers flowed during folding such that the slaty cleavage remained normal to the axis of maximum finite shortening.

The greywacke layers in the Chelmsford Formation buckled under a lateral compression and formed concentric folds. In concentric folds, the strain is extensional in the outer arc and compressional in the inner arc. These arcs are separated by a neutral surface of no strain near the centre of the layer (Park 1983). Strain is greatest at the fold hinges and decreases toward the limbs. Thus, the fracture cleavage in the greywacke layers formed in the outer arcs and in the hinge areas of the folds.

FOLDS

Folds occur in rocks of the South Range and the central belt. There is a change in fold style from southeast to northwest.

In the South Range, isoclinal mesoscopic similar folds are present in the basal member of the Onaping Formation (Stevenson 1960). The axial planes dip steeply to the southeast and the folds are overturned to the northwest. The Vermilion and Errington Mines are located in the southwestern part of the basin (see Figure 9.1 for location). In the mines, rocks of the upper part of the Onaping Formation and those of the Onwatin Formation display macroscopic, similar folds that are isoclinal, doubly plunging, and overturned to the northwest with the axial planes dipping to the southeast. Some of the folds are asymmetrical with a long southeastern limb and a short northwestern limb (Thomson 1957; Martin 1957).

North of Vermilion Lake, mesoscopic folds occur in slaty cleavage of the Onwatin Formation. Most of the folds plunge to the northeast, but some plunge northwest and others, southwest.

The Sudbury Basin may be divided by an arcuate axis that is convex to the northwest. Fold axes in the Chelmsford Formation trend parallel to this axis and vary in strike from N48°E in the southwest to N72°E in the northeast (Rousell 1972). The folds display an *en échelon* pattern, the limbs generally dip < 45°, axial planes are vertical, wave lengths vary from approximately 150 m to as much as 1500 m, and most of the folds are doubly plunging. The folds formed by the flexural-flow mechanism; the thick greywacke layers flexed and the thin pelitic layers flowed. The folds are nearly concentric in style, and geometrically, are plane non-cylindrical folds. In map view, anticlines are narrow and synclines are broad. In concentrically folded

piles, anticlines became broader upward and narrower downward; synclines exhibit the opposite geometry (Ramsay 1967). This suggests that the preserved rocks of the Chelmsford Formation are near the lower part of a unit that was originally thicker. Minor northwesterly trending cross folds are also present in the formation.

In summary, folds in the South Range are isoclinal, similar, and overturned to the northwest; those in the central part of the basin are relatively open, concentric, and upright. This change in fold style is due to a decrease in deformation intensity toward the northwest, and because rocks in the South Range were at a lower level than those in the central belt during deformation.

KINK BANDS

Rotation of the tectonic foliation in the Onaping Formation produced kink bands that are present at several localities along the entire length of the South Range. Kink bands at the Gordon Lake Road, located at the southwestern corner of the basin (shown as KB on Figure 5.1), are described in detail by Rousell (1980), and those at the other sites have a similar orientation and geometry.

The kink bands are narrow with a maximum width of 4 cm and have an average width of 0.8 cm. The average distance between kink bands is approximately 20 cm, but locally are so closely spaced as to be penetrative. The external foliation strikes northeasterly and dips moderately steeply to the southeast. The internal foliation within the kink bands has been rotated to the vertical and beyond so as to dip steeply to the northwest. The kink band boundaries or kink planes dip at shallow angles to the northwest and the hinge lines trend east-northeasterly and are nearly horizontal. The average orientation of these elements are plotted on the stereogram of Figure 5.2. Microfractures and former open spaces (presently filled by quartz and calcite) occur at the kink band boundaries and the boundaries are locally offset in a step-like fashion.

The angle between the external foliation and the kink planes (α) is approximately 60° in kink bands in slates and phyllites formed by the fixed-boundary mode of propagation. If slip between foliation planes within the kink band is the sole operating mechanism, then rotation proceeds until the angle between the foliation plane inside the kink band (α) equals β ; the kink band is then locked and no further rotation can take place. In the Onaping kink bands, α is unusually large (average is 84°), exceeds that of β (average is 73°), and 86% of the kink bands are over-rotated (see Figure 5.2). Thus, Onaping kink bands differ from those found in slates and phyllites.

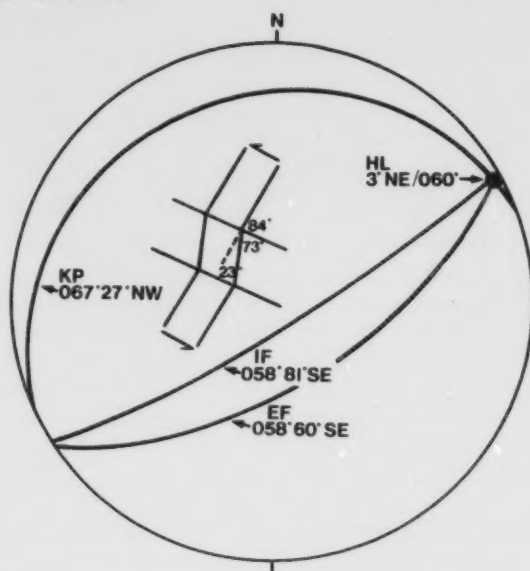


Figure 5.2. Lower hemisphere equal-area plot of the average orientation of elements of kink bands located on the Gordon Lake Road. EF—external foliation, IF—internal foliation, KP—kink plane, and HL—hinge line. Insert is a profile view of the average Onaping kink band (after Rousell 1980).

The mechanism of formation of the Onaping kink bands is by slip along closely spaced foliation planes and along the margins of fragments together with solution and redeposition and possibly ductile flow of the matrix. The large α angle is a function of the nature of the planar anisotropy as it is more widely spaced and less well developed than in slates and phyllites. The amount of shortening achieved by kinking is trivial and is approximately 0.7% parallel to the external foliation. The axis of the maximum principal stress that formed the kink bands at the Gordon Lake Road trends normal to the long axis of the basin and plunges southeasterly between 15° and 50°. The kink bands probably formed during a late stage of the Penokean Orogeny.

FAULTS

The map of the Sudbury Basin prepared by Burrows and Rickaby (1930) shows only 3 faults. A detailed account of faulting is given by Thompson (1957) and numerous faults are shown on his map; several of those indicated are questionable. The fault pattern on the 1:50 000 map accompanying this volume is similar to that of Thompson (1957), but includes several additional faults. For purposes of discussion, all faults are classified in terms of the orientation of fault traces with respect to the long axis of the basin as follows: longitudinal, transverse, and diagonal.

Longitudinal Faults

Several northeasterly striking longitudinal faults occur at the southwestern corner of the Basin where they offset rocks of the Sudbury Igneous Complex. Card and Hutchinson (1972) suggested that these faults are part of the Murray Fault System located north of Lake Huron. The maps of Thomson (1957), Card (1968), and this volume extend these longitudinal faults through the central part of the basin to the northeastern end, where they bend to the southeast and pass out of the basin at the junction between the South and East Ranges. The proposed traces of the faults, in the central part of the basin, are along drift-covered valleys, and it is difficult to be certain that these features are the site of faults. The area where these faults strike to the southeast is covered by thick glacial deposits and contains few outcrops. The orientation of some longitudinal faults has been deduced from the attitude of schistosity supposedly produced by shearing (Thomson 1957). Caution should be exercised because some "schistosity" might actually represent a tectonic foliation formed by a process other than shearing.

In the southwestern corner of the basin, the Cameron Creek Fault has produced a left-lateral strike separation of approximately 3400 m in the granophyre. Thomson (1957) considered the fault to be a steeply dipping reverse fault with a large net slip, and noted that drill cores cutting the fault contain recemented breccia, silicification, and quartz-feldspar-calcite veins. The fault and the granophyre have attitudes of approximately N40°E, 75°SE; and N9°W, 42°NE, respectively. Assuming the slip is entirely dip slip, then the dip slip is 2800 m and the throw 2680 m, south-side up. Northeast of Vermilion Lake, a branch of the Cameron Creek Fault supposedly occurs at the contact between the Onaping Formation and the Onwatin Formation (Thomson 1957; Map 2491, back pocket). Rocks of the Onaping Formation form a southeasterly facing cliff at the contact. Thomson (1957) suggested that this feature may represent a fault-line scarp of the Cameron Creek Fault. The cliff faces are parallel to a well-developed joint set (Rousell and Everitt 1981). A more plausible explanation is that the cliffs formed by mass-wasting along joint surfaces.

Faults in the Vermilion and Errington Mines are considered to lie within the Vermilion Lake fault zone (Thomson 1957). The faults in the Vermilion Mine dip approximately 35°SE, whereas those in the Errington Mine dip 67° to 77°SE. The faults are parallel to the axial plane of folds and the amount of dip slip varies between a few 10s of m to as much as 150 m.

At the southwestern margin of the basin, the Fairbank Lake Fault (FBLF on Figure 5.1) branches into 3 faults, each of which displaces the Sudbury Igneous

Complex. Evidence for the northeasterly continuation of the fault, south and southeast of Vermilion Lake, includes outcrops of silicified gouge and the presence of red alteration, brecciation, chlorite shears, and quartz stringers in drill cores (Thomson 1957). The fault trace passes through the Gordon Lake "gold mine" (see Figure 9.1). The large mass of quartz-rich rock on the property is interpreted as a fragment derived from the basal member of the Onaping Formation and faulted into its present position (Rousell 1982).

In northeastern Balfour Township, a longitudinal reverse fault occurs at the contact between the Chelmsford Formation and the Onwatin Formation. The south-side is up and the throw is only a few m (Rousell 1972). Several minor longitudinal faults in the Chelmsford Formation display slickensides indicating that the latest movement on them was horizontal (Rousell 1972).

Transverse Faults

The rocks of the North Range are cut by north-northwesterly striking faults of the Onaping set that dip steeply and, in general, display a left-lateral strike separation. The fault traces are marked by prominent topographic lineaments. The faults extend a considerable distance north of the basin where, in general, the strikes swing a few degrees toward the north-south direction. The faults do not cross the central part of the basin.

The strike of the Fecunis Lake Fault (FLF on Figure 5.1), the most westerly of the set, swings from N23°W in the North Range to N5°W north of the basin. The fault dips steeply to the west (Cowan 1968), the left-lateral strike separation is approximately 800 m and the vertical component of displacement, west side up, may be in the order of 150 m (Card and Meyn 1969). According to Burkhard O. Dressler (Geologist, Ontario Geological Survey, written communication, 1983), the Fecunis Lake Fault, a right-lateral transverse fault located 3 km to the east of the Fecunis Lake Fault, and a northeasterly striking thrust fault located 2 km northeast of the basin, outline a block that was displaced upward and to the northeast (see Map 2491, back pocket, for fault locations).

Movement on the Sandcherry Creek Fault (SCF on Figure 5.1) has produced a left-lateral strike separation of 450 m on the base of the Sudbury Igneous Complex in the North Range. Approximately 9 km to the northwest and along the fault trace, the Foy Offset Dike has a right-lateral strike separation of 700 m. There are several transverse faults northeast of the Sandcherry Creek Fault that indicate relatively minor strike separations. The most easterly transverse fault in the North Range strikes north-south; north of the basin the strike of this fault, unlike the other transverse faults, swings to the northwest. In the East Range, a

left-lateral fault that strikes N10°W may be a member of the Onaping set.

North of the basin, faults of the Onaping set are parallel to Matachewan dikes of pre-Huronian age (Meyn 1973). The faults may represent Archean extension fractures that were reactivated after the formation of the basin (Rousell and Everitt 1981). The later movement could be left-lateral strike slip, a vertical displacement with the west side up relative to the east side, or an oblique slip. Perhaps movements of different magnitudes and directions occurred at different times (Card and Meyn 1981).

Diagonal Faults

A set of right-lateral diagonal faults occurs in the central part of the basin. These faults strike N25° to 30°E, locally displace fold axes and longitudinal faults, or are themselves displaced by longitudinal faults (Thomson 1957). None of the faults cut rocks of the Sudbury Igneous Complex. Minor northeasterly trending diagonal faults are also present in the East Range.

The Falconbridge Fault is a prominent feature in the Falconbridge Mine (Davidson 1948; Lothead 1955). The fault strikes east and dips steeply north from the surface to a depth of approximately 365 m where the dip reverses to 60° to 80°S. The fault is at the contact between norite and "greenstone" and the ore shoots occur in the hangingwall. The fault may be older than the norite and there is evidence of pre- and post-ore faulting. According to Davidson (1948), the slip along the fault is oblique with the north side displaced upward and westward relative to the south side. The Falconbridge Fault supposedly joins the Fairbank Lake Fault; however, the sense of displacement of the dip slip component of the latter fault is south-side up.

JOINTS

Numerous joint sets exist in the rocks of the Sudbury Basin and they formed in mechanically inhomogeneous rocks. Some joint sets are geometrically related to certain structural elements. Several of these elements trend from west-northwest to north-northwest; joint sets, related to these elements, overlap in orientation. Some joint sets can be related to particular episodes in the evolution of the basin (see Table 5.1), whereas the age of other sets is uncertain.

Rousell and Everitt (1981) measured the orientation and intensity of development of joints at 456 stations located throughout the basin. Plumose structures and slickensides were seldom observed, and this prevented a direct classification of the joints. There are as many as 7 joint sets at a given station and joint sets at virtually every orientation are present throughout the basin. A summary plot of the average orientation of

major joint sets in 9 subareas (Figure 5.3) indicates that sets with northwesterly strikes and steep dips predominate. The data for Figure 5.3 were obtained from maxima on contoured stereograms. The length of a given strike line is proportional to the strength of the corresponding maximum on the stereogram for that subarea. Subareas 1 to 8 are within the Sudbury Igneous Complex and Onaping Formation; subarea 9 is within the Onwatin and Chelmsford Formations.

Table 5.2 lists the major joint sets shown in Figure 5.3 and indicates their relationship, if any, with structural elements or rock units. The rocks of the East Range are the most intensely jointed. Joint sets are geometrically related to a local fault, to the strike of rock units, to diabase dikes, and to the norite-Footwall contact. Mitchell and Mutch (1957) noted 3 well developed joint sets in the norite of the Hardy Mine (located in subarea 4). These are: parallel to the plane of the Footwall contact of the norite; parallel to the strike and normal to the dip of the same contact; and vertical and striking normal to the contact. The same set occur on the surface in the North Range. However, the set that is parallel to the plane of the Footwall contact is too weak to plot on Figure 5.3. Other sets in the North Range strike parallel to the strike of faults of the On-

aping set or are parallel to diabase dikes. The dominant joint set in the South Range is vertical and strikes normal to the strike of the tectonic foliation. Of the 4 sets of joints in the central belt, 1 set is parallel to diabase dikes, another set represents cross joints on folds, and 2 other sets cannot be related to structural features.

TECTONIC HISTORY OF THE SUDBURY BASIN

An outline of the tectonic history of the basin is given in Table 5.1. The basin represents a remnant of an original structure that may have been 80 km in diameter (Dence 1972). The change from the pelagic sedimentation of the Onwatin Formation to turbidite sedimentation of the Chelmsford Formation suggests that orogenic activity began soon after the formation of the basin (1849 Ma). The 3 joint sets in the Sudbury Igneous Complex of the North Range, geometrically related to the norite-Footwall contact, may have formed during the cooling of the Complex. The absence of these joints in the Sudbury Igneous Complex of the South Range may be because they were obliterated by later ductile deformation.

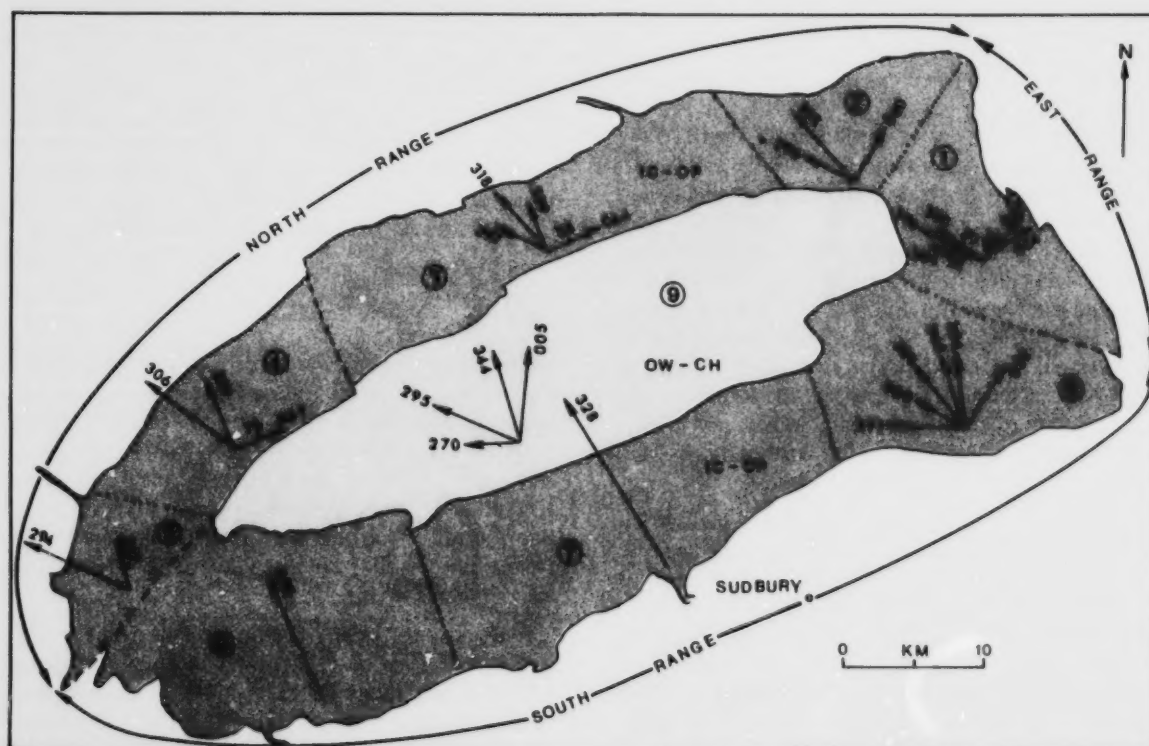


Figure 5.3. Map showing the average orientation of major joint sets. The length of the strike lines (arrows) are proportional to the strength of maxima on contour diagrams. Dips are vertical unless otherwise indicated. Subareas are shown as numbers enclosed by circles. IC-OP = Sudbury Igneous Complex and Onaping Formation; and OW-CH = Onwatin and Chelmsford Formations.

The Sudbury Basin was deformed by the Penokean Orogeny approximately 1750 Ma (Gibbins and McNutt 1975). The deformation was due to a 'push' from the southeast and directed toward the northwest (Brocoum and Dalziel 1974; Rousell 1975). The Onaping Formation of the South and East Ranges yielded by flow. The formation was shortened toward the northwest and tectonically thickened, a prominent tectonic foliation and lineation formed, and rocks at the top and bottom of the unit developed isoclinal, similar folds. A foliation and lineation also formed in the granophyre, but only locally in the norite. Farther to the northwest, rocks of the Chelmsford Formation buckled and formed open, concentric folds. A slaty cleavage formed in rocks of the Onwatin Formation and in pelitic layers in the Chelmsford Formation. A fracture cleavage developed in greywacke beds in the Chelmsford Formation. Still farther to the northwest, the deformation was slight as only a local and weak foliation occurs in the Onaping Formation of the North Range.

The weighted average near-surface dip of the base of the Sudbury Igneous Complex is 42° SE in the North

Range and 65° NW in the South Range (Souch, Podolsky *et al.* 1969). In the South Range, the complex locally dips steeply to the southeast. Paleomagnetic studies by Sopher (1963) suggested that the 2 ranges originally had the same dip; reverse movement along the longitudinal faults rotated the South Range and steepened the dip. The paleomagnetic data of Morris (Chapter 19, this volume) indicate that the original dip of the North and South Ranges was between 20° and 30° SW, and that of the East Range 15° SW. Stevenson and Colgrove (1968) and Naldrett *et al.* (1970) suggested that deeper sections of the Sudbury Igneous Complex are exposed in the South Range than in the North Range. They ascribe this to upthrust of the South Range along the longitudinal faults. According to Souch, Podolsky *et al.* (1969), Naldrett *et al.* (1970), and Card and Hutchinson (1972) the total vertical displacement along these faults was 4.8 km, 6.4 km, and 1.6 km, respectively.

The longitudinal faults cannot be traced through the central part of the basin with certainty. Well documented faults in the Vermilion and Errington Mines

TABLE 5.2: MAJOR JOINT SETS IN THE SUDBURY BASIN.

SUBAREAS	SET ORIENTATION	REMARKS
1.	040° 68°NW 054° 90° 284° 72°NE 296° 90° 303° 30°NE	strikes parallel to a local fault strikes normal to strike of rock units — parallel to diabase dikes strikes subparallel to strike and normal to the dip of the norite-footwall contact
2.	030° 90° 296° 90° 318° 90°	— parallel to diabase dikes strikes parallel to strike of a fault of the Onaping set
3.	064° 58°NW 297° 90° 318° 90° 339° 90°	strikes parallel to strike and normal to the dip of the norite-footwall contact parallel to diabase dikes strikes parallel to strike of a fault of the Onaping set strikes parallel to strike of a fault of the Onaping set
4.	067° 76°NW 306° 90° 337° 90°	strikes parallel to strike and normal to the dip of norite-footwall contact strike normal to strike of norite-footwall contact strikes parallel to a fault of the Onaping set
5.	294° 90° 347° 90°	parallel to diabase dikes —
6.	335° 90°	strikes normal to the strike of the foliation
7.	328° 90°	strikes normal to the strike of the foliation
8.	see note 3	strikes normal to the strike of the foliation
9.	005° 90° 270° 90° 295° 90° 334 90°	— — parallel to diabase dikes cross joints on folds

Notes

1. See Figure 5.3 for location of subareas
2. —Joint set not related to a structural element
3. Strike of the foliation varies in subarea 8

have maximum vertical displacements of only 152 m. The above led Rousell (1975) to suggest that the role of reverse faulting in the uplift of the South Range has been exaggerated. Most of the uplift was accomplished by flowage, folding, and rotation. During the later stages of the Penokean Orogeny, the forward motion at the surface exceeded that at depth. This steepened and uplifted the South Range, rotated the foliation to dip consistently to the south, overturned mesoscopic folds at the base of the Onaping Formation (Stevenson 1960) and macroscopic folds at the top of the formation (Thomson 1957) to the northwest, and overturned the Onaping-Onwatin contact to the northwest (Thomson 1957). The lack of foliation in the South Range norite, and the presence of the longitudinal faults at either end of the South Range, suggest that the relatively brittle norite yielded by reverse faulting. These faults died out as they passed into the ductile rocks above the norite.

The exact time of formation of the kink bands in the Onaping Formation is not known; they may have formed at a late stage of the Penokean Orogeny. The orientation of the maximum principal stress that formed the kink bands, in terms of trend and plunge, is 150° and 15° to 50° SE (Rousell 1980). The trend is perpendicular to the long axis of the basin and approximately parallel to the maximum principal stress direction associated with the Penokean Orogeny.

The prominent joint set in the South Range, vertical and striking north-northwest, may represent post-orogenic extension fractures. The basin may have undergone regional uplift with extension parallel to the long axis of the basin and with a residual maximum principal stress parallel to that of the Penokean Orogeny.

Joints parallel to diabase dikes (1250 ± 50 Ma, Van Schmus 1975) are apparently extension fractures and indicate an extension of the basin along a north-northeast south-southwest axis in Middle Proterozoic time. West-northwesterly trending diabase dikes are abundant in the Superior Province to the northwest of the basin suggesting that this extension was a regional phenomena.

In the North Range, faults of the Onaping set strike from 336° to 000° and display a left-lateral strike separation. North of the basin, these faults trend approximately 345° and are parallel to Matachewan dikes of pre-Huronian age (Meyn 1973). The Onaping faults may represent Archean extension fractures that were reactivated after the formation of the basin. The later movement could be a left-lateral strike slip, a dip slip with the west side up, or an oblique slip. A joint set is parallel to the faults; the joints are shear fractures if they are genetically related to the faults.

Rousell (1975) suggested that the embayment of the East Range, and the bulges at both ends, may have

been formed by opposing stresses from the southwest and the northwest that produced a pincer-like squeeze. Dence and Popelar (1972) and Dressler (1982) present evidence that Wanapitei Lake was formed by meteorite impact. A K-Ar date of 37 Ma (Winzer *et al.* 1976) suggests a Paleogene age for the event. The northeastern margin of the East Range is only 2 to 4 km southwest of the shoreline of the lake, and the arcuate shape of the East Range is parallel to the trend of lakes between the East Range and Lake Wanapitei. Dence and Popelar (1972) considered that the arcuate shape of the East Range is tectonic in origin. However, impact could have embayed the East Range, produced the bulges at either end, and rotated the foliation to strike parallel to the axes of the bulges.

PRE-DEFORMATION SHAPE OF THE BASIN

Several attempts have been made to estimate the shape of the Sudbury Basin prior to deformation. The basin was originally less elliptical than its present form in plan view; most investigations suggest that it was never circular.

The presence of dominant paleocurrent directions to the west-southwest and the lack of facies change along the basin axis led Cantin and Walker (1972) and Rousell (1972) to conclude that the sediments of the Chelmsford Formation were not deposited in a circular or semi-circular basin, but rather in an elongate trough. The axis of the trough was parallel to the present axis of the basin with the paleoslope to the west-southwest. Rousell (1972) unrolled the folds in the Chelmsford Formation and suggested that the original outcrop belt of the formation should be extended 1.6 km in a southeasterly direction.

Peredery (1972) noted that meltrock bodies at the base of the Onaping Formation in the North Range occur in clusters that have the shape of an equilateral triangle in plan view. Meltrock bodies in the deformed rocks of the eastern part of the South Range also have an overall triangular shape, except that the triangles are skewed to the northwest. Fragments in the Onaping Formation in the undeformed North Range are sub-equidimensional; those in the South Range are deformed and are the shape of triaxial ellipsoids with an average axial ratio of 1:4:8. Peredery (1972) estimated the strain in the South Range by the change of shape of equilateral triangles to skewed triangles. The degree of area change, in plan view, was estimated from the shape change of the fragments. Peredery (1972) concluded that, prior to deformation, the contact between the norite and the Footwall rocks was approximately 15.3 km southeast of the present contact. The ratio of the long axis/short axis of the present basin is 2.2. This same ratio, for the pre-deformation basin

is 1.5. Assuming an initial spherical shape, deformed fragments with axial ratios of 1:4.8 have undergone the following approximate strain: a 65% shortening in a direction normal to the foliation, a 26% extension in a direction normal to the lineation and parallel to the foliation, and a 152% extension parallel to the lineation.

The weighted-average near-surface dips of the outer margin of the Sudbury Igneous Complex are 42° in the North Range and 65° in the South Range (Souch, Podolsky *et al.* 1969). The reader should consider that these 2 planes are projected to depth so as to intersect along an axis and that the South Range is rotated about this axis so as to dip 42°NW. The outer margin of the Complex, projected to a horizontal plane, would then be 10.4 km southeast of the present outer margin.

Finite-strain analysis on flattened concretions in the Chelmsford Formation and on elongate rock and mineral fragments in the Onaping Formation led Brocoum and Dalziel (1974) to suggest that the deposition area of the Chelmsford Formation and the Sudbury Basin were circular or nearly so prior to deformation. The absence of basic data in the paper makes it difficult to directly verify these conclusions.

According to Brocoum and Dalziel (1974), the lack of a preferred grain elongation in the foliation plane of the Chelmsford Formation indicates deformation is in the field of flattening with maximum shortening normal to the foliation plane. These authors further proposed that the flattening is spectacularly displayed by concretions which, apart from local variable shapes, are always flattened in the foliation surface, and therefore, must have been originally spherical or nearly so. The assumption of an original spherical shape is actually incorrect; objects will always be flattened in the foliation plane if the X/Z axial ratio of the strain ellipse exceeds the X/Z ratios of initial ellipses of any orientation. Finite strain analysis (Brocoum and Dalziel 1974) suggests that the Chelmsford Formation was shortened 30% in a direction normal to the foliation plane, was extended 10% subhorizontally in the foliation plane, and was extended 40% subvertically in the plane of the foliation (no volume change assumed).

Concretions in the Chelmsford Formation display a variety of shapes including spherical, elliptical, pipelike, as coalesced beads, and as lenses parallel to bedding (Rousell 1972). These concretions occur only in greywacke and never in argillite-siltstone. The "foliation" of Brocoum and Dalziel (1974) is actually a fracture cleavage and it does not appear to represent a plane of flattening. Primary sedimentary structures in the greywacke have not undergone an intense flattening-type strain. The greywacke layers form concentric folds; the fracture cleavage may have developed as a result of extension in the outer arc of hinge areas. Compression in the inner arc may have flattened the

concretions. Accordingly, flattened concretions may be a local feature. Strain analysis of them cannot be directly used to calculate the shortening of the Chelmsford Formation.

In the Onaping Formation of the South Range, the tectonic foliation dips steeply southeast, and a lineation formed by elongate mineral and rock fragments, lies in the foliation plane and plunges steeply to the southeast. Finite strain analysis (Brocoum and Dalziel 1974) using the fragments, suggests the formation was shortened by 40% normal to the foliation, shortened by 30% normal to the lineation and in the foliation plane, and extended by 140% parallel to the lineation (assuming no volume change).

Rousell (1975) drew attention to some of the difficulties involved in calculating the finite strain of deformed fragments from the Onaping Formation of the South Range. The X, Y, and Z axes of the fragments were measured in 2 thin sections from a single specimen. X and Z are the long and short axes in a thin section cut normal to the foliation and parallel to the lineation, and the Y and Z are the long and short axes in a section normal to the foliation and lineation. The mean, maximum, and minimum X/Z ratios are as follows: glass—13.7, 35.3, and 3.6; quartzite—4.3, 15.5, and 1.1; and quartz—1.7, 3.3, and 1.0. The mean, maximum, and minimum Y/Z ratios are as follows: glass—3.6, 8.0, and 1.1; quartzite—2.0, 6.4, and 1.0; and quartz—1.6, 2.3, and 1.0. Assuming that the fragments were originally spherical and there has been no volume change, strain calculations for the mean values of glass fragments are as follows: X—273% extension, Y—2% shortening, and Z—73% shortening. Similar calculations for the mean value of quartzite fragments are: X—110% extension, Y—2% shortening, and Z—51% shortening. There is considerable variation in the degree of strain between the 3 fragment types. The relative deformation of glass, quartzite, and quartz can be described as strong, moderate, and weak, respectively. There is also a variation in the amount of strain in a given fragment type. Glass fragments are the most elongate and it might appear that the strain in glass would best reflect the strain in the unit as a whole. The undeformed glass fragments have very irregular shapes, including a shard-like shape. The glass fragments were most likely to have been deposited in a molten or semi-molten state. They may have become flattened and welded by compaction (Stevenson 1972) and, if so, they assumed a dimensional preferred orientation prior to deformation. The 3 axes of individual fragments cannot be directly measured; shapes must be characterized in terms of ratios. Finally, there is a variation in the intensity of development of the tectonic foliation and lineation in the South and East Ranges. Accordingly, finite strain varies from place to place.

The rocks of the North Range appear to be essentially undeformed. If the North Range represents an arc of a circle, then this circle extends to Pointe au Baril, a locality approximately 113 km south of Sudbury (Rousell 1975). This preposterous location suggests that the basin was not originally circular. Paleomagnetic studies of Morris (Chapter 19, this volume) suggest that the original configuration of the basin was that of an open syncline, elliptical in plan view, and with a gentle plunge to the southwest. The North and South Ranges dipped between 20° and 30°, the East Range dipped approximately 15°SW, and the southwestern end of the basin was subhorizontal. There is no paleomagnetic evidence to suggest that the basin was ever circular.

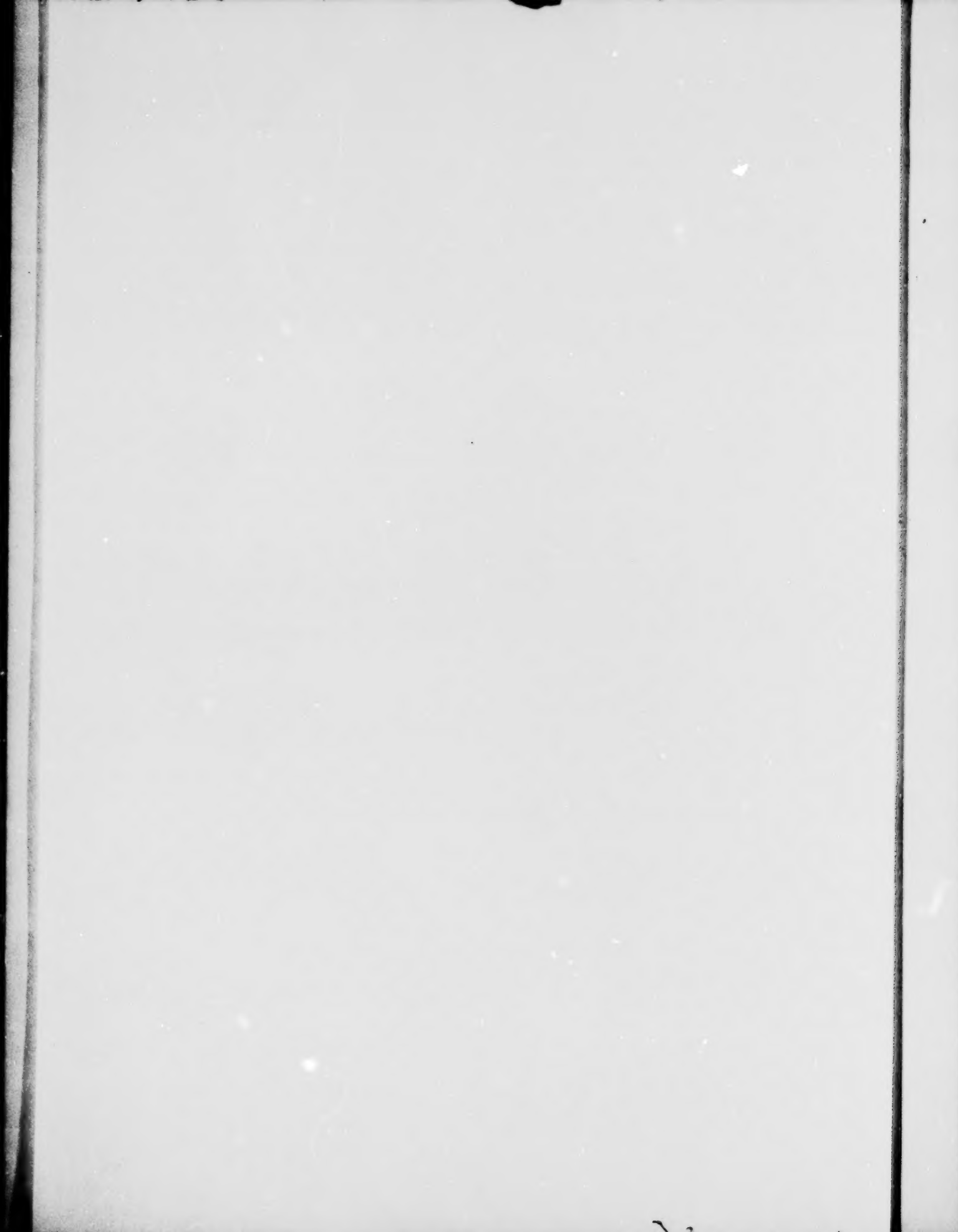
Folds in the Chelmsford Formation plunge and this suggests that the basin was shortened somewhat along its major axis. The East Range is convex to the southwest. Prior to the Wanapitei Event, the East Range was probably convex to the northeast with the base of Sudbury Igneous Complex, in the central part of the Range, possibly 4 km to the northeast of the present contact.

In conclusion, the available data suggest that prior to deformation, the Sudbury Basin was an elliptical basin with a southwesterly paleoslope and with the northwestern and southeastern margins dipping inward at approximately 30°. The southeastern margin was approximately 15 km to the southeast of its present position and the northeastern margin was approximately 4 km to the northeast of its present position. The original basin was 62 km long and 41 km wide and had a ratio of long axis/short axis of 1.5.

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CHAPTER 6

The Effects of the Sudbury Event and the Intrusion of the Sudbury Igneous Complex on the Footwall Rocks of the Sudbury Structure

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ABSTRACT

Megascopic features related to the Sudbury Event are ring fractures north of the Sudbury Igneous Complex. Such features also include a steepening of dip, and an eventual overturning of stratified rocks in the vicinity of the southern crater rim. Foliation and jointing in the Footwall rocks do not show clear evidence that they are related to an impact feature.

Shatter cones occur all around the Complex. Other shock-metamorphic features such as planar features and kink bands in Footwall rock-forming minerals also exist and indicate a decrease in shock pressure with distance away from the Complex.

Sudbury Breccia occurs all round the Complex, and for distances as great as 80 km away from it. Lithological and chemical evidence suggests that it originated essentially *in situ* prior to the emplacement of the Complex. The breccia was formed mainly by brittle fracture, comminution of Footwall rocks in an explosive event, and by later readjustments of the earth's crust.

The Footwall Breccia is heterolithic and para-autochthonous to autochthonous. It occurs at the lower contact of the Complex. Brecciation and shock metamorphism are related to the Sudbury Event.

Contact metamorphism affected all the Footwall rocks including the breccias near the lower contact of the Complex in a zone up to 1.2 km wide.

The effects of the Sudbury Event on the Footwall rocks can be explained by assuming an impact origin for the Sudbury Structure.

INTRODUCTION

The Sudbury Structure lies near the junction of 3 structural provinces of the Canadian Shield. These are the Superior, Southern, and Grenville Provinces. The lithologies, structure, and metamorphic features of the Sudbury area span approximately 2 Ga of complicated geological history. Features related to the Sudbury Event, which is considered by the author to have been a volcanic explosion or the impact of a meteorite, are superimposed upon older structural and metamorphic characteristics. Such features have been affected by later geological events such as the later phases of the Hudsonian-Penokean Orogeny.

The author defines the term "Footwall" to consist of rock units characterized by deformational and metamorphic features related to the Sudbury crater-forming event. The "Footwall" is approximately 35 to 40 km, possibly 80 km wide north and east of the Sudbury Igneous Complex, and is about 9 to 40 km wide south of the Complex. The northern, eastern, and southwestern limits of the "Footwall" are defined by

the first occurrences of the Sudbury Breccias. The southern and southeastern limits of the "Footwall" are defined by the Grenville Front Boundary Fault.

Structural, deformational, and metamorphic features are described in this chapter that are relevant to the origin of the Sudbury Structure. In the first part of the chapter, large scale structures, not described in other chapters of the Sudbury Volume, are dealt with. The second section describes the breccias. The third section describes shock-metamorphic features. The fourth section describes the contact-metamorphic effects found in the Footwall rocks near the Sudbury Igneous Complex.

This paper does not address the origin of the Sudbury Structure. This is covered by Muir (Chapter 21, this volume) and Peredery and Morrison (Chapter 22, this volume). Interpretations of the features observed in the Footwall rocks that are relevant to the origin of the Sudbury Structure were avoided by the author so as to provide as unbiased an account as possible.

Throughout the following account, the author uses many terms that are specific to Sudbury geology. These terms are defined in the chapter on the General Geology of the Sudbury Area (Dressler, Chapter 4, this volume). A geological map (Map 2491, back pocket) should be consulted by the reader unfamiliar with the geography of the Sudbury area.

STRUCTURES OF THE SUDBURY FOOTWALL

In this section, regional and local structural features of the Footwall will be discussed that may be related to the origin of the Sudbury Structure. The regional geotectonic setting of the Sudbury Structure is discussed by Card *et al.* (Chapter 2, this volume); the structure of the Sudbury Igneous Complex and the Sudbury Basin is described by Rousell (Chapter 5, this volume).

Megascopic Structures

A ring graben or ring fault system and an overturned crater collar, similar to those known to exist in the footwalls of several cryptoexplosion craters or meteorite impact craters, are found in the Footwall rocks of the Sudbury Structure.

On Landsat satellite images, a distinct ring fracture that is located at a distance of 18 to 27 km from the Sudbury Igneous Complex can be recognized (Figure 6.1). The ring fracture position coincides with several outliers of rocks of the Huronian Supergroup, is crudely concentric with the North Range Sudbury Igneous Complex, and is similar in appearance to ring

graben or ring fault zones known to exist around several terrestrial and lunar craters. Two terrestrial examples showing these structures are the Wells Creek Structure in Tennessee (Stearns *et al.* 1968) and the Manicouagan Structure in Quebec. Ring and multi-ring systems are common on the surface of the earth's moon and other bodies in the solar system (Taylor 1982).

No comprehensive detailed study of this outer fault zone has been made. Only 3 large outcrop areas at the southern limit of the zone, just east of the Benny "Greenstone" Belt, which occurs northwest of the Sudbury Igneous Complex, have been visited by the author. At 2 of the 3 outcrop areas, vertical fault planes with vertically plunging slickensides were found. The strike of these faults is subparallel to the strike of the fault zone seen on the satellite image at these locations. These limited observations do not allow the postulation of a continuous ring fault or ring graben system around the entire structure; however, they are significant enough to be mentioned here.

The South Range crater collar consists mainly of the Huronian Supergroup and granitic rocks of the Creighton and Murray Plutons. The Huronian rocks are folded and faulted, but it is not possible to establish in the Sudbury area to what extent the large scale structures of these rocks are the result of conventional, endogenic processes (Hudsonian-Penokean Orogeny), or are the result of the Sudbury crater-forming event. At a few places in the South Range near the Sudbury Igneous Complex, for instance, just south of the Ellen pit in Denison Township (Card 1968; Map 2119), and south of Falconbridge and Happy Valley in Falconbridge and Garson Townships (Map 2491, back pocket), the collar rocks dip vertically or may even be overturned. Farther away from the Complex, dip directions are away from the Complex and decrease in magnitude, such as in Falconbridge and Garson Townships, where the dip changes from 90° to 35° south

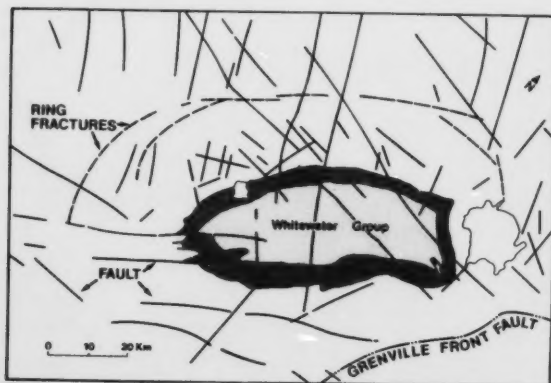


Figure 6.1. Ring fractures in North Range Footwall (from Landsat images).

over a distance of about 1750 m. This steepening of dip, including the eventual overturning of stratified rocks in the vicinity of the "crater", has been observed at several craters. Examples of such craters are the Vredefort Structure in South Africa and the Decaturville Structure in Missouri (Offield and Pohn 1977).

Mesoscopic Structures

FOOTWALL ROCK FOLIATIONS

The pre-Sudbury event foliations of the East and North Range Footwall rocks are represented by 4 stereograms in Figure 6.2. The gneissosity in all North and East Range sectors dips steeply. This is not consistent with a pre-Sudbury domal structure as suggested by Speers (1957).

Schistosity and gneissosity south of the Sudbury Igneous Complex also dip steeply and strike approximately parallel to the South Range Complex. These features are post-Sudbury Igneous Complex in age because the South Range Complex has been affected by the same deformation as the South Range Footwall.

FOOTWALL JOINTS

The joint orientations of the North Range Footwall rocks have been studied by the author. The objective was to determine the nature and radial extent of possible modifications of the regional joint patterns due to the Sudbury crater-forming event. Figure 6.3 shows 22 equal area stereograms of joints in the North Range Footwall rocks. Stereograms of Sector 14 (Dressler 1980), of Sectors 15 to 20 (Dressler 1982), Sector 21 (Dressler 1979), and Sector 22 (Meyn 1977) have been obtained from published Ontario Geological Survey reports. The other stereograms are based on joint measurements taken by junior assistants during 1979 to 1982 aerial mapping programs undertaken by the Ontario Geological Survey.

The regional northwest to west-northwest trend is most evident in stereograms of sectors farthest away from the Sudbury Igneous Complex, and is also visible in some stereograms of sectors near the Complex, for instance in Sector 9. Other stereograms, however, show the regional trend only faintly, or not at all, and are characterized by a more random distribution of joint directions (Sectors 2, 3, 5, 8, and 10). The stereograms of Sectors 15 to 20 show regional trends and also reflect the Wanapitei Lake impact crater (Dence and Popelar 1972; Dressler 1982). The stereograms of Sectors 12 and 13, and possibly Sector 4, show indications of preferred jointing parallel to the lower contact of the Sudbury Igneous Complex.

In Sector 1, east-striking, steeply north-dipping joints are parallel to 90° to 110° shearing observed by the author in many places west of the Sudbury Igneous

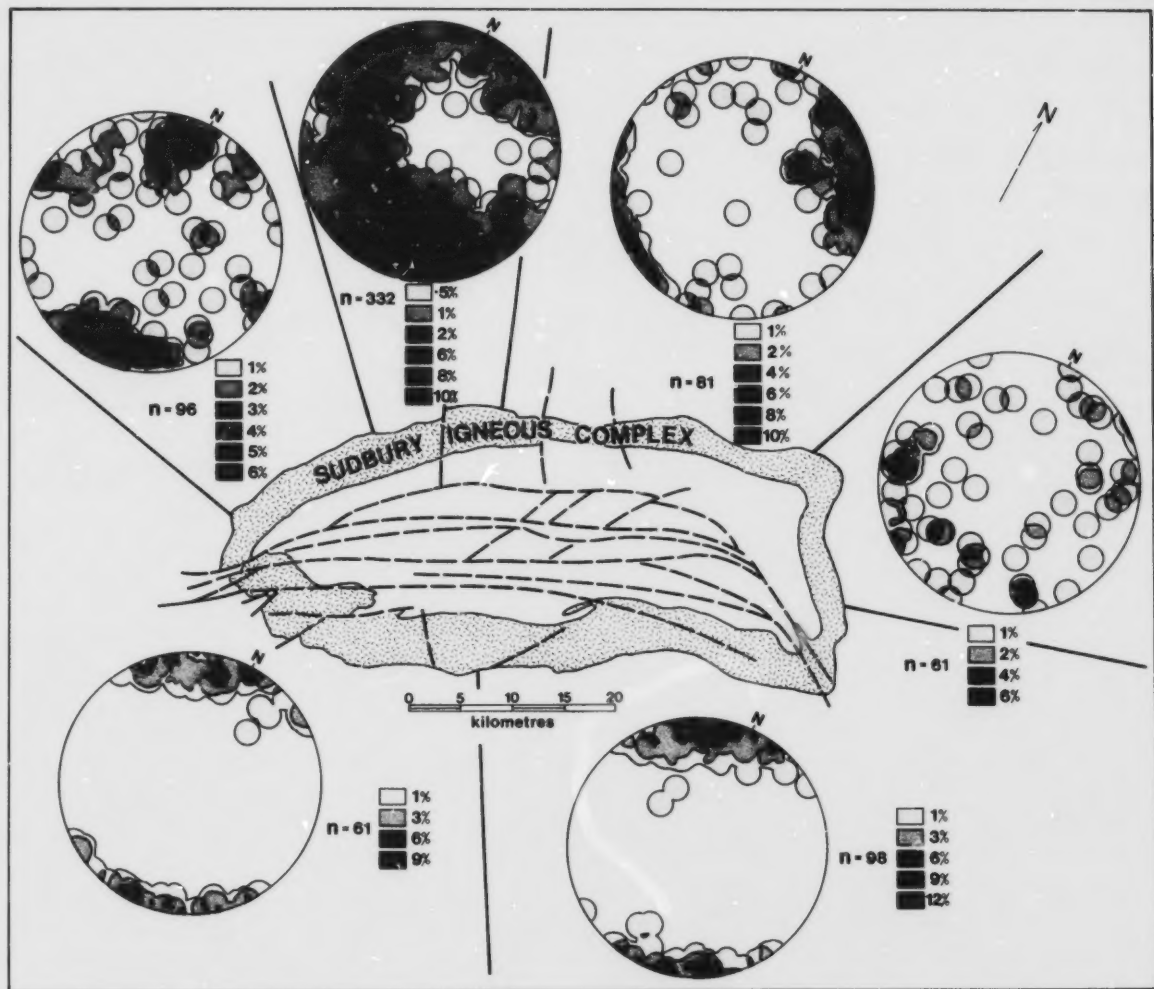


Figure 6.2. Stereograms for Footwall rock foliations.

Complex. A broader maximum strikes approximately parallel to the fault zone that cuts across the southwestern Sudbury Igneous Complex, and indicates a dip of approximately 70° to 80° for the joints and the fault zone.

The joint patterns north and east of the Sudbury Igneous Complex can be interpreted as being characterized by a random strike and steep dips that are superimposed on regional trends near the Sudbury Igneous Complex. East of the Sudbury Igneous Complex, around Wanapitei Lake, the joint patterns are the result of regional deformation, the Sudbury Event, and the later Wanapitei Lake impact. No obvious effect on regional joint patterns can be recognized at distances greater than 30 km measured in directions radiating from the lower contact of the Complex.

SHOCK METAMORPHISM

The term shock metamorphism describes all the

changes affected in rocks and minerals which result from the passage of high pressure shock waves. The passage of such waves through the rocks causes permanent structural damage to minerals and rocks. Natural shock waves are produced by the instantaneous transfer of kinetic energy from an impacting meteorite to the target rocks, or, as some more conventional researchers maintain, by endogenic, volcanic processes to the enveloping rocks.

In the Sudbury Footwall rocks, microscopic and macroscopic shock-metamorphic features are common. In the South Range Footwall rocks, microscopic features are all but destroyed due to regional metamorphic recrystallization.

Shatter Cones

Shatter cones (Photo 6.1), first discovered by Branco and Fraas (1905) in the Steinheim impact crater in southern Germany, are conical fracture surfaces with

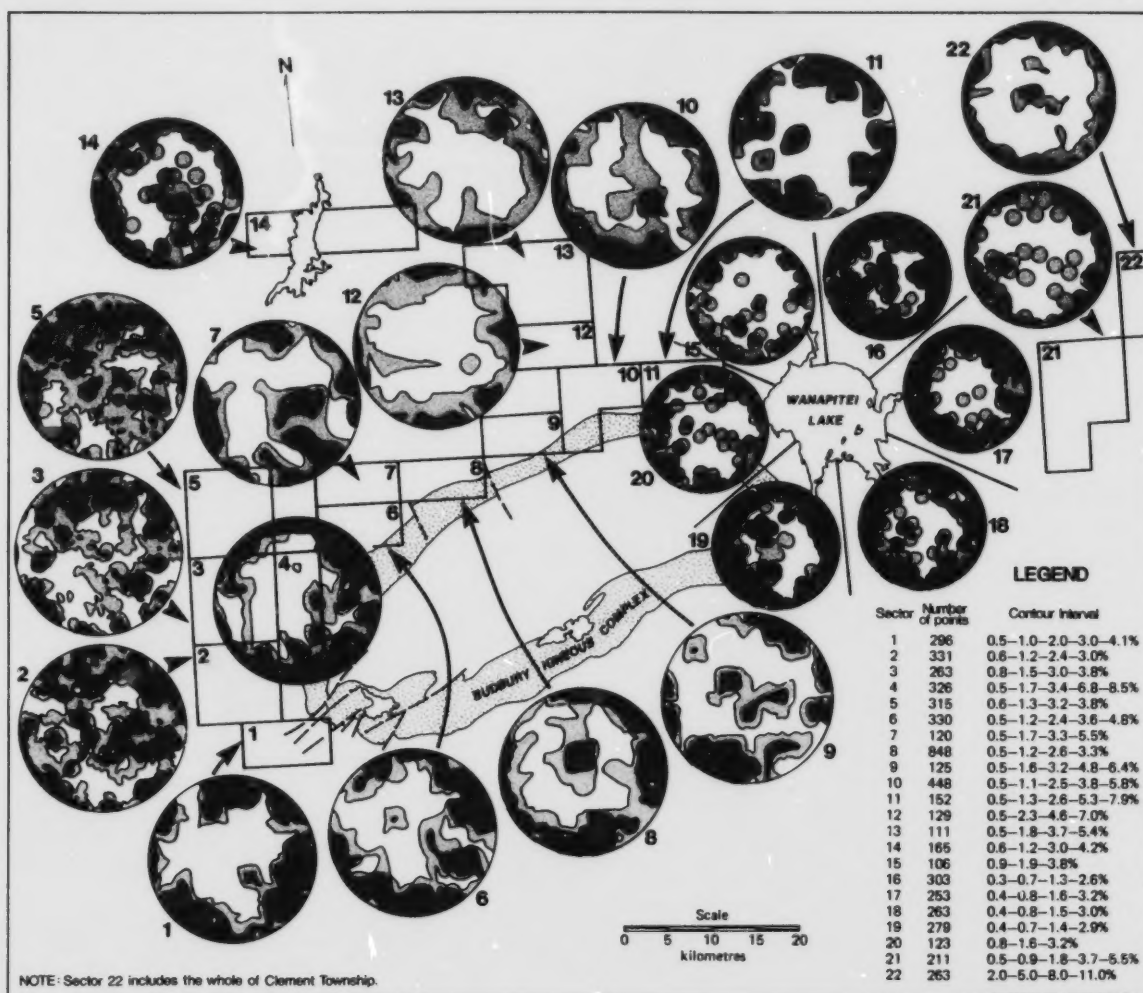


Figure 6.3. Stereograms for Footwall rock joints.

striae that fan from an apex (Dietz 1968, 1972). The striae are sharp grooves between intervening, rounded ridges. The Sudbury shatter cones are up to 3 m long (Guy-Bray and Geological Staff 1966).

The origin of shatter cones is a matter of debate. In several publications, Dietz (1959, 1962, 1964, 1968, 1972) advocated a meteorite impact origin for the Sudbury shatter cones. Milton (1977) stated that "one must be unusually broadminded to entertain hypotheses for shatter coning other than that it results from shock generated by impact". Broad minded researchers, however, still exist. Sage (1978) proposed a volcanic origin for the Slate Islands structure where shatter cones also occur. Fleet (1979) proposed a conventional tectonic origin for the Sudbury shatter cones.

Shatter cones occur around the entire Sudbury Igneous Complex for distances as much as 17 km (Guy-Bray and Geological Staff 1966) away from it. Figure

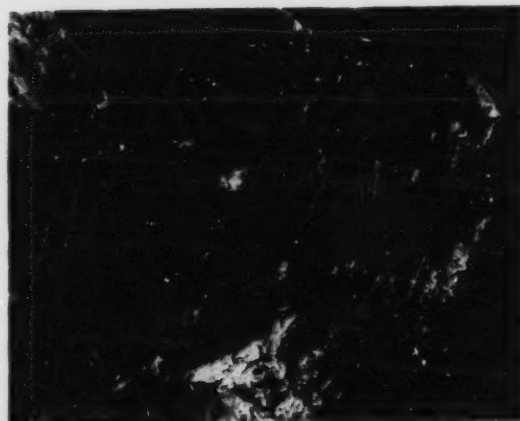


Photo 6.1. Shatter cones in arenite of the Mississagi Formation. Ramsey Lake Road near Laurentian University Campus. Filter is 5 cm in diameter. (Photography courtesy of W. Meyer, Sudbury).

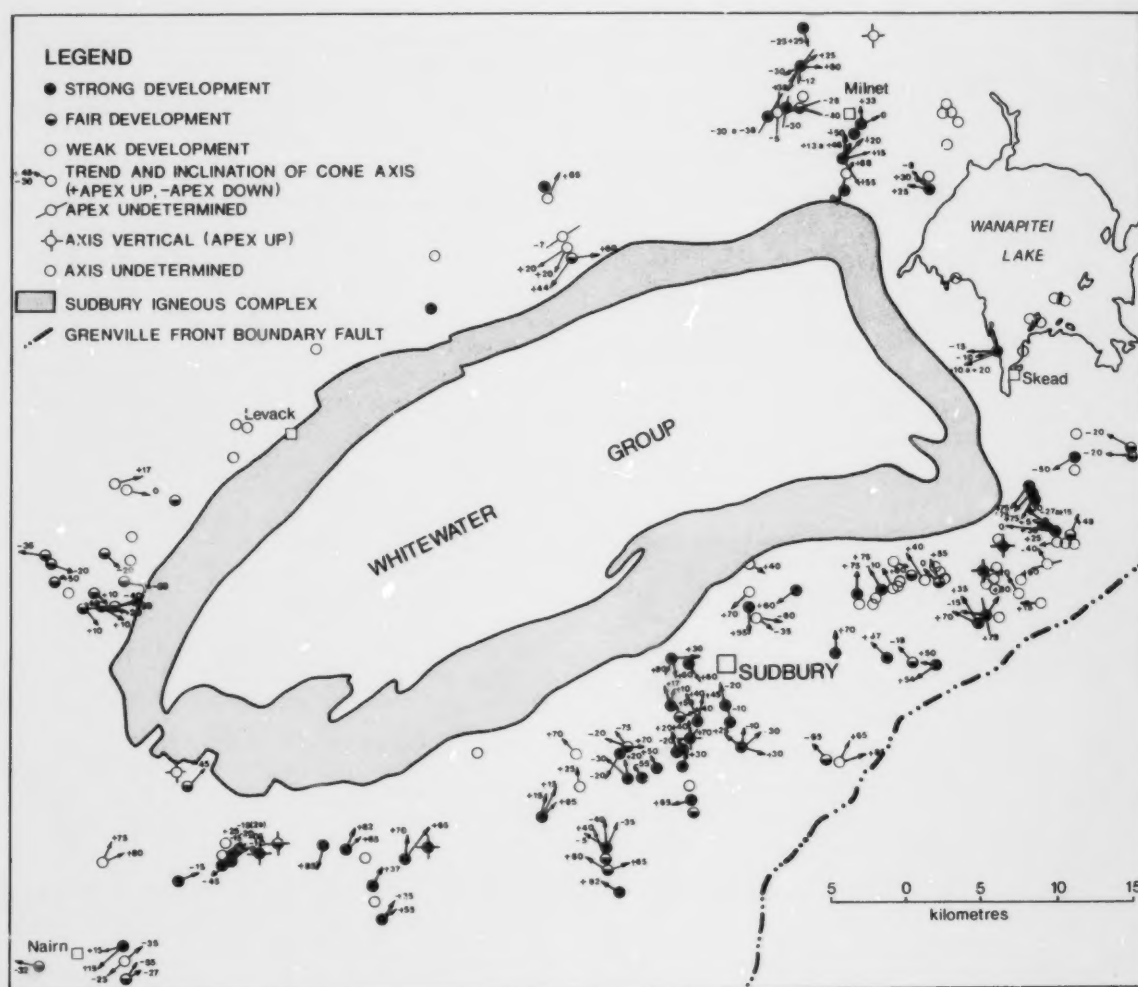


Figure 6.4. Shatter cone occurrences and orientations. After Guy-Bray and Geological Staff (1966), and additional observations by the author.

6.4 is based on Figure 1 of Guy-Bray and Geological Staff (1966). Approximately 60 additional shatter cone locations have been observed and added to this figure by the author. Many of the conical features point toward the Sudbury Basin, but random orientations and opposite directions at one and the same shatter cone location are also common.

Roddy and Davis (1977) stated that the apices may point in random directions, "but after the host rocks are stereographically rotated back to their original position, the cones invariably point toward the shock wave source area, and indicate the source came from above rather than below ground (Milton *et al.* 1972; Howard and Offield 1968)". The observation of shatter cone orientations in 2 opposite directions at some locations around the Sudbury Igneous Complex and also at the Gosses Bluff (Australia), Sierra Madera (Texas), Steinheim (Germany), and other structures

(F. Hörz, Experimental Planetology Branch, NASA Johnson Space Center, Houston, personal communication, 1983) is not in agreement with this statement.

Shock-Metamorphic Features in Minerals

Kink bands in biotite (Photo 6.2) and other micaceous minerals are the first sign of shock-induced mineral deformation seen under the microscope and indicate weakly shocked rocks. Kink bands occur in shocked rocks formed by meteorite impact and observed in nuclear explosion craters (Cummings 1968), but also occur in micas of tectonically deformed rocks. In shock metamorphosed rocks, kink bands coexist with other shock-metamorphic features characteristic of a rather wide range of shock pressures. In strongly shocked rocks, all biotite grains are kinked. At still higher shock

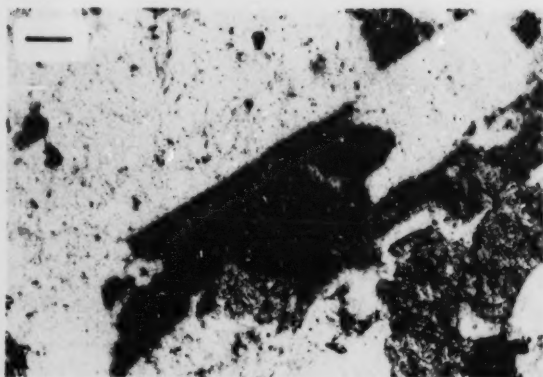


Photo 6.2. Kink bands in biotite gneiss, Levack Township. Crossed polarizers. Scale 0.1 mm.

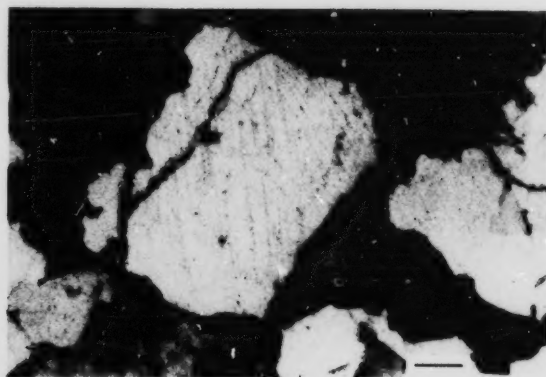


Photo 6.3. Planar features in quartz. Granitic rock, North Range Footwall. Crossed polarizers. Scale 0.2 mm.

pressures, the birefringence and pleochroism of biotite are reduced and biotite becomes oxidized. The oxidation is probably secondary, and is caused by the shock-induced rise in temperature. In the Footwall around the Sudbury Igneous Complex, kinked micas are common, and were observed up to 10 km away from the Sudbury Igneous Complex, and may possibly occur at even greater distances than this.

Quartz in the Sudbury Footwall rocks exhibits well-preserved shock-metamorphic features. Weakly shocked quartz is characterized by fracturing oblique or parallel to crystallographic planes (von Engelhardt *et al.* 1969; Dressler 1970). Shock waves of 100 and more kbar peak pressures (Hörz 1968; Müller and De-fourneaux 1968) produce shock lamellae (Photo 6.3). Weakly shocked quartz contains one or a few sets of lamellae commonly parallel to the (0001), (1013), and/or (0113) crystallographic planes. Up to 11 parallel sets (Robertson *et al.* 1968) per quartz grain were observed in severely shocked quartz grains from

Canadian craters and von Engelhardt and Bertsch (1969) noticed up to 18 sets in quartz from the Ries crater in Germany.

In the Sudbury Footwall rocks, the author observed up to 3 sets per quartz grain.

Robertson and Grieve (1977) estimated the shock attenuation at terrestrial impact structures by comparing experimental results for various shock levels with observations made at 3 Canadian structures (Brent Crater, Slate Islands, and Charlevoix Crater). These authors distinguish 4 deformation types (A, B, C, and D) based on characteristic planar feature frequency and orientation in quartz, and a fifth type characterized by rocks that show no planar features in quartz. Rocks of this fifth type may contain shatter cones. The Robertson and Grieve (1977) method was used to roughly estimate the shock pressures in rocks outside the contact metamorphic aureole in Levack Township. The results are shown in Table 6.1 and Figure 6.5.

Diaplectic quartz glass and the 2 SiO₂ high pressure modifications, coesite and stishovite, have not been observed in the Footwall rocks. These minerals are metastable and, if present in the first place, did not survive contact and regional metamorphism.

Shock-metamorphic features in plagioclase have been well studied (von Engelhardt *et al.* 1969; Stöffler 1967; Chao 1968b; Dressler 1970). Pressures below approximately 100 to 150 kbar do not produce any typical shock-metamorphic features other than fracturing of crystals, bending of twin lamellae, and possibly development of twins. These features are not necessarily diagnostic of such shock.

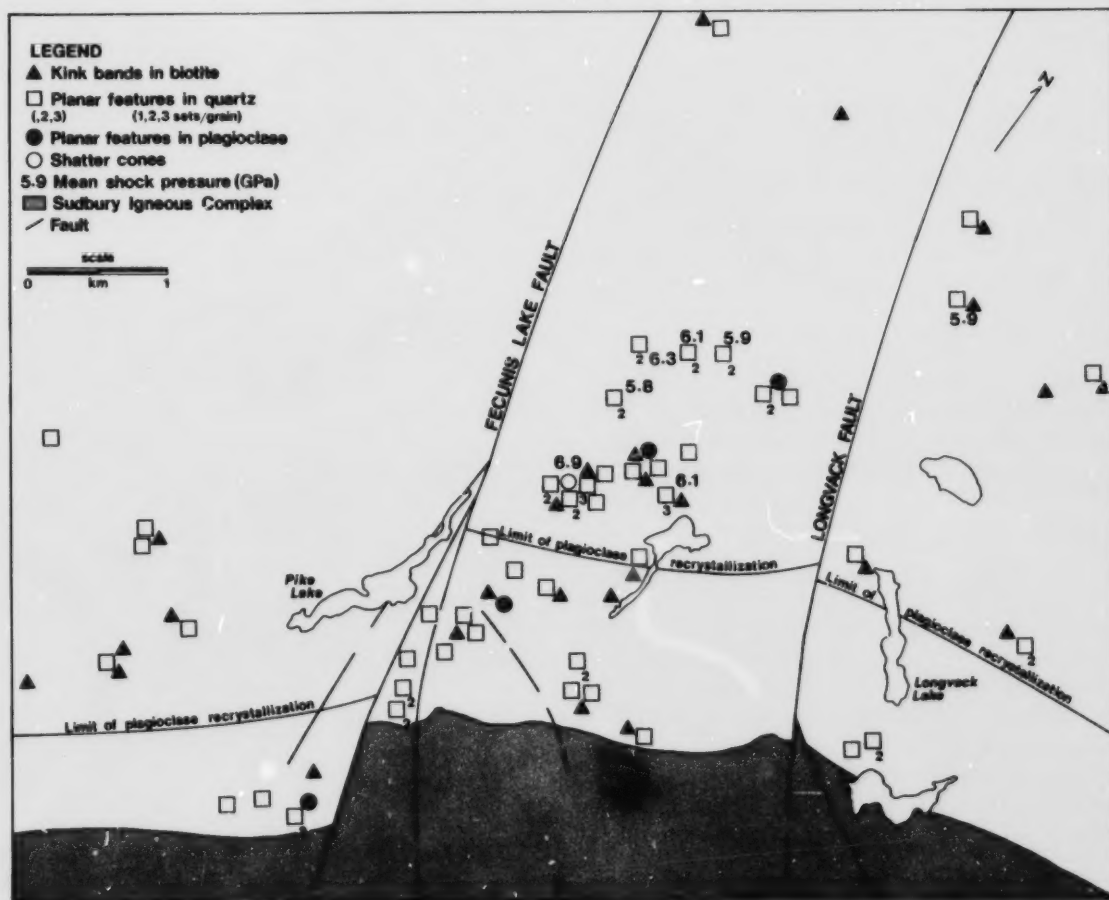
Pressures between approximately 150 and 300 kbar (von Engelhardt *et al.* 1967) produce planar features and isotropizations within plagioclase grains. Above 300 and under 500 kbar, whole plagioclase crystals become diaplectic glass (maskelynite), and above 500 kbar, normal glass of plagioclase composition is produced. Recent shock experiments (Ostertag 1981) with single crystals of various feldspars indicate that at shock pressures of 280 to 300 kbar all feldspar crystals except for 1 perthitic microcline were changed into diaplectic glass. In more recent experiments, Ostertag (1983) obtained planar features at 140 kbar in plagioclase and at 105 kbar in alkali feldspars.

In the Footwall rocks of the Sudbury Structure, fracturing of plagioclase crystals and bending of plagioclase twin lamellae are commonly observed. Planar features (Photo 6.4) are also present. Partial or complete diaplectic isotropization was not observed in Footwall plagioclase. Photo 6.5, however, shows a concentric extinction pattern in a shock-metamorphic plagioclase, possibly representing recrystallized maskelynite. Potassic feldspar (Photo 6.6) shows the same shock-metamorphic features as plagioclase.

TABLE 6.1: SHOCK PRESSURE IN NORTH RANGE FOOTWALL ROCKS FROM QUARTZ DEFORMATION (METHOD OF GRIEVE AND ROBERTSON 1976; ROBERTSON AND GRIEVE 1977).

DISTANCE TO SUDBURY IGNEOUS COMPLEX-FOOTWALL CONTACT (km)	TOTAL NUMBER OF QUARTZ GRAINS	% QUARTZ WITH PLANAR FEATURES	TYPE A DEFORMATION	TYPE B DEFORMATION	TYPE C DEFORMATION	MEAN SHOCK PRESSURE (GPa)*	REMARKS	SHOCK DEFORMATION IN QUARTZ
1.44	93	11.8	8	2	1	?	Partly recrystallized (0001), (1010) and (1012) observed	
1.84	53	9.3	3	2	1	6.1		Deformation Type Characteristic planar feature orientation
1.84	48	31.4	10	4	1	6.9		
2.48	89	6.7	5	1	-	5.8	-	Shatter cones, but no planar features
2.70	46	21.7	8	2	-	6.3	A	(0001)
2.88	50	16.0	6	2	-	6.1	B	(1013) (2241), (1011)
3.04	58	12	6	1	-	5.9	C	(0111), (1122)
4.40	88	14.8	13	-	-	5.9	D	(1012)

* 1 GPa = 10 Kbar

**Figure 6.5. Shock-metamorphic features in the Footwall rocks of Levack Township.**

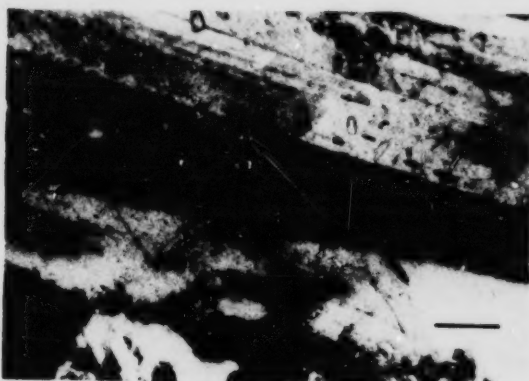


Photo 6.4. Planar features in plagioclase (hardly visible on photograph, 2 sets indicated by arrows). Gneiss, Levack Township. Crossed polarizers. Scale 0.1 mm

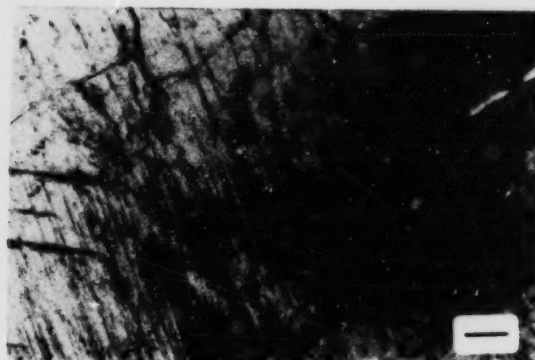


Photo 6.6. Planar features in potassic feldspar. Granite. North Range. Scale 0.05 mm.

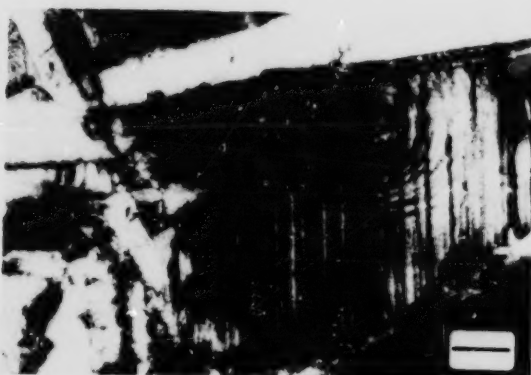


Photo 6.5. Concentric extinction pattern in shock-metamorphic plagioclase. Gneiss, Levack Township. Crossed polarizers. Scale 0.1 mm.

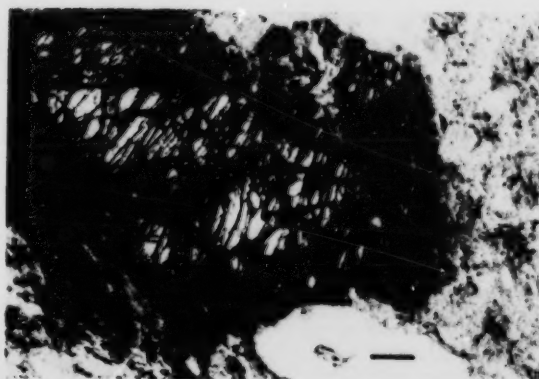


Photo 6.7. Strongly fractured garnet. Gneiss, Levack Township. Plane polarized light. Scale 0.2 mm.

Shock-metamorphosed hornblende and pyroxene exhibit deformation bands and planar features; apatite displays a parting or cleavage parallel to (1011). Garnet is strongly fractured (Photo 6.7) in rocks approximately 0.9 km north of the Sudbury Igneous Complex in Levack Township.

Vesiculated country rocks are known to occur as inclusions in the suevite, the impact breccia of the Ries Crater in south Germany (von Engelhardt *et al.* 1969), and as parautochthonous and allochthonous rocks in the Manicouagan Crater in Quebec (Murtaugh 1976). Similar fragments occur also in the breccias of the Onaping Formation (W.V. Peredery, Staff Geologist, Inco Limited, personal communication, 1983) and in volcanic breccias (H.U. Schmincke, Professor, Ruhr University, Bochum, personal communication, 1983).

Filled vesicle-like features were noticed in a thin section (Photo 6.8) of a gneissic migmatite specimen collected from the North Range at a site approximately

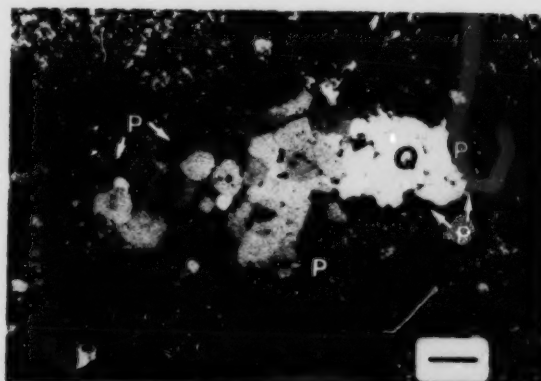


Photo 6.8. Vesicle in migmatitic gneiss of North Range filled with hypidiomorphic quartz (Q) aggregate that is rimmed by a fine plagioclase (P) seam. Crossed polarizers. Scale 0.2 mm.

1.2 km east of West Cameron Lake. The elongate or irregularly shaped "vesicles" are up to 2 mm in size. These consist of xenomorphic to idiomorphic quartz rimmed by small plagioclase grains. Small amounts of

the breccia is somehow related to the Sudbury Structure. Therefore, it should be possible to relate the orientation of the breccia bodies to the geometry of this structure. Card (1978a, p. 195) studied the Sudbury-Manitoulin area southwest of the Sudbury Igneous Complex, and stated "that there is a suggestion of both radial and concentric patterns about the Nickel Irruptive" (Sudbury Igneous Complex). Similar trends were not recognized by T. Muir (Geologist, Ontario Geological Survey, personal communication, 1981) and the author of this chapter north and east of the Complex. This is possibly due to the different structural properties of the rocks north and south of the Sudbury Igneous Complex. The rock units in the south, in general, trend parallel to the Sudbury Igneous Complex boundary. Since breccia bodies commonly follow contacts between lithological units, the concentric breccia distribution may reflect only pre-breccia lithological trends. In the north, in the predominantly granitic rocks, gneisses, and migmatites, random pre-Sudbury Breccia lithological and structural weaknesses, such as rock contacts, foliations, joints, and faults, caused more random orientations of breccia bodies. The large breccia bodies can be mapped in only

a few places, such as in part of the well-exposed South Range Footwall terrain. The longest and largest breccia body investigated by the author hosts the Frood and Stobie Mine orebodies, and is approximately 11 km long (see Map 2491, back pocket). It is neither concentric nor radial with respect to the Sudbury Igneous Complex, but, in general, follows the trend of the Huronian lithologies.

The orientation of many breccia bodies is not known because of the commonly discontinuous exposures of the rock. No attempt was made by the author to document the orientation of irregularly shaped breccia bodies. The orientation of 739 breccia dikes, however, is shown in the 6 stereograms of Figure 6.7. A clear and convincing correlation between orientation maxima and the shape of the Complex is not possible in most stereograms. In the southeastern stereogram, a maximum exists for breccia orientations subparallel to the trend of the Complex. The other South Range stereogram is similar. The East Range stereogram shows steeply dipping, randomly oriented, breccia dikes. Concentric breccia orientation is indicated by the eastern, and possibly also the western

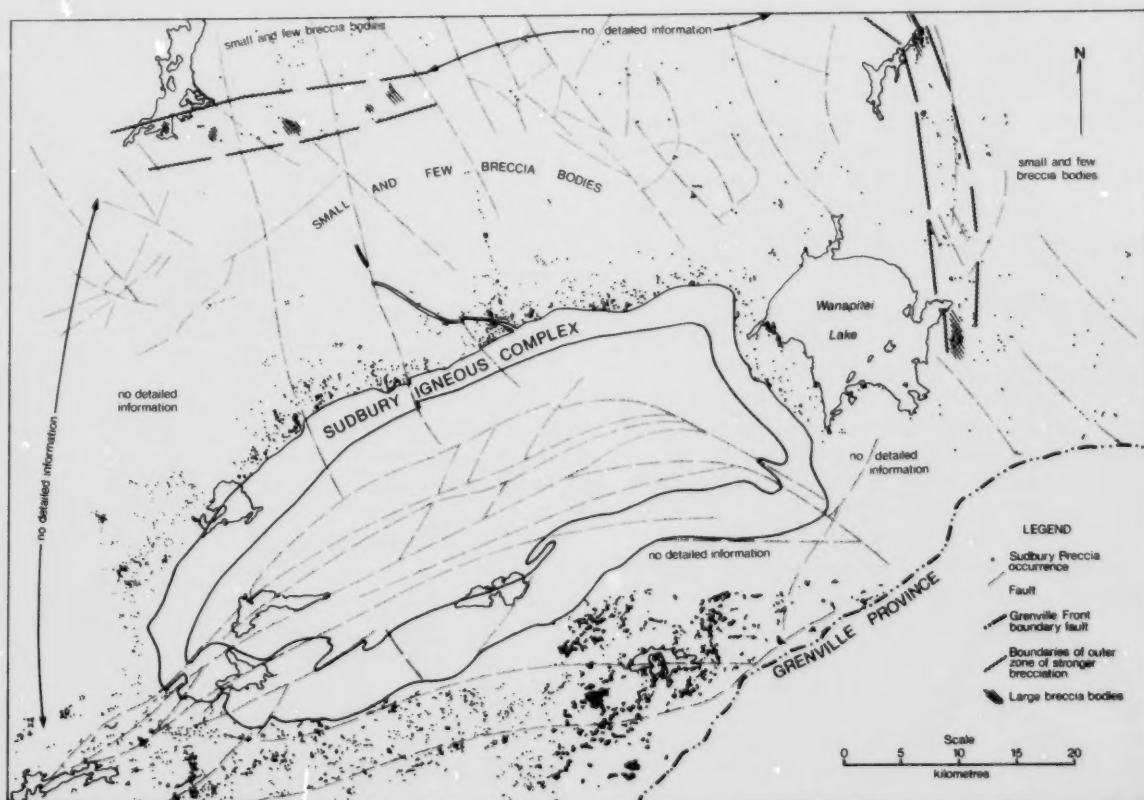


Figure 6.6. Sudbury Breccia occurrences (information from published and unpublished Ontario Geological Survey maps) (see also Figure 22.4 of Peredery and Morrison, Chapter 22, this volume).

carbonate may be present in the centres, and in one case, a stubby apatite crystal was observed. In hand specimen, the "vesicles" cannot be recognized and distinguished from pink, recrystallized feldspars.

The features represent either amygdules, which were originally gas-filled cavities, or strongly shocked, diaplectic, and later recrystallized quartz-feldspar aggregates (W.V. Peredery, Staff Geologist, Inco Limited, personal communication, 1983), or, most likely, a shock-induced, normal quartz-feldspar melt trapped in an otherwise still solid rock (G. Graup, Max Planck Institut für Chemie, Mainz, personal communication, 1983).

Zoning of Shock-Metamorphic Features in the Footwall

The size and structural complexity of the Sudbury Structure make impractical the study of shock-metamorphic features and the zonal distribution of them around the entire Sudbury Igneous Complex. The South Range Footwall rocks were subjected to a higher rank, post-Sudbury Event metamorphism than the North Range rocks (Card 1978b; Dressler, Chapter 4, this volume). For these 2 reasons, a small section of the North Range Footwall in Levack Township was chosen for a more detailed investigation of the zoning of shock-metamorphic features (see Figure 6.5). More than 100 thin sections indicate that a crude zoning of such features can be recognized in the rocks. Very close to the contact, and up to about 500 m (or about 1000 m in the Strathcona Mine sector) north of the contact, shock-metamorphic features, however, are commonly no longer visible, or are present only as relicts due to a strong contact-metamorphic recrystallization.

Planar features in quartz were observed by the author for as much as 5.5 km north of the Sudbury Igneous Complex, but may be present as far as approximately 8 km away as is shown by Dence (1972). Two or more sets of lamellae occur up to about 3 km north of the Sudbury Igneous Complex. The shock pressures responsible for the formation of the planar features in the quartz grains were estimated for a few samples using Robertson and Grieve's (1977) method (see Table 6.1). These pressures are shown at the appropriate locations in Figure 6.5. The mean shock pressures appear to be somewhat low compared with shock experiments based on this method (Hörz 1968; Müller and Defourmeaux 1968). The result, in general, however, indicates a decrease in shock pressure with distance from the Sudbury Igneous Complex. Planar features in plagioclase occur up to 2.9 km north of the Sudbury Igneous Complex. These are absent at closer distances due to the strong contact-metamorphic recrystallization of the country rocks.

BRECCIAS IN THE FOOTWALL OF THE SUDBURY STRUCTURE

The breccias in the Footwall of the Sudbury Igneous Complex are some of the most intriguing rocks related to the Sudbury Structure. A study of these breccias may reveal an understanding of the origin of the Sudbury Structure. In spite of many studies, the origin of the breccias remains the subject of considerable debate.

Sudbury Breccia

The areas around the Sudbury Igneous Complex host many unusual breccia bodies known as Sudbury Breccia, previously also called Sudbury-type breccia, Levack Breccia, or Common Sudbury Breccia. The breccias have been the subject of several publications (examples are: Fairbairn and Robson 1942, 1943; Speers 1957; Card 1978a; Muir 1981, 1983; Dupuis *et al.* 1982).

DISTRIBUTION

The Sudbury Breccia occurs as numerous, irregular, or crudely tabular bodies around the Sudbury Igneous Complex. It is abundant within a distance of 5 to 10 km from the Sudbury Igneous Complex, but it is known to occur much farther away. For instance, in Emo, Rhodes, and Botha Townships, it occurs up to 25 km northwest of the Sudbury Igneous Complex (Dressler 1980), in the Chiniguchi Lake area, 50 km northeast of the Complex (Dressler 1981b); in Janes and McNish Townships (Dressler 1979), about 50 km to the east; and near Espanola (Card 1978a), about 28 km west of the Complex. Peredery and Morrison (Chapter 22, this volume) indicate that the breccias exist also 80 km northeast of the Sudbury Igneous Complex. Close to the Complex, the breccia bodies, in general, are larger and more abundant than farther away. Evidence, however, exists for the presence of 2 specific zones of increased brecciation about 20 to 25 km and 80 km away from the Complex. These zones are characterized by more, commonly much larger breccia bodies than in the annuli which are about 10 to 20 km and about 35 km wide. Figure 6.6, showing the breccia distribution around the Sudbury Igneous Complex, is based on the work of many investigators. In this figure, breccia bodies (large and small) appear to be more common south of the Sudbury Igneous Complex than to the north. This, however, is not the case, and the apparent distribution merely reflects outcrop density that is greater in the south than in the north.

ORIENTATION

The geographical distribution of the Sudbury Breccia around the Sudbury Igneous Complex indicates that

North Range stereograms. The central North Range stereogram exhibits a more or less random distribution of steeply to vertically dipping breccia dikes.

In both the North and South Range Footwall, the Sudbury Breccia dikes dip steeply or vertically. The South Range measurements were taken from rocks located at least 2 km south of the Sudbury Igneous Complex, so as to avoid measuring and recording breccia orientations in overturned lithologies. Nevertheless, the South Range data are very similar to North and East Range data. This probably indicates that the major deformational event of the Hudsonian-Penokean Orogeny is pre-Sudbury Event in age. A distinct tectonic foliation, however, is present in many South Range breccias, and is related to later phases of this orogeny.

DESCRIPTION

Sudbury Breccia bodies range in size from large zones up to 11 km long to small patches that are only a few cm across or to seams a few mm thick. The breccias

form irregularly shaped bodies, veins, and dikes. In a few places, breccia dikes appear to radiate away from more irregularly shaped breccia bodies (Figure 6.8). The contacts with the host rocks are sharp.

In Figure 6.9, several Sudbury Breccia bodies are sketched. Offsets along breccia dikes, as seen in sketch A, are not common. The dikes may follow lithological contacts (sketch E), but in the granitic terrain of the North Range, do not seem to be controlled in this way. Several *en echelon* dikelets (sketches B and C) were observed in a few places. The dikes bifurcate and send apophyses into the host rocks (sketches D and F). The area between bifurcating dikes may be strongly brecciated as is shown in sketch D of Figure 6.9. In a very few places, deformed clasts within the breccia bodies and dikes indicate shearing. In sketch F, a few clasts imbedded in the thicker dike XX show strong plastic deformation due to shearing parallel to XX. The matrix in this dike shows flow lines parallel to XX, and wraps around the fragments. No flow lines, however,

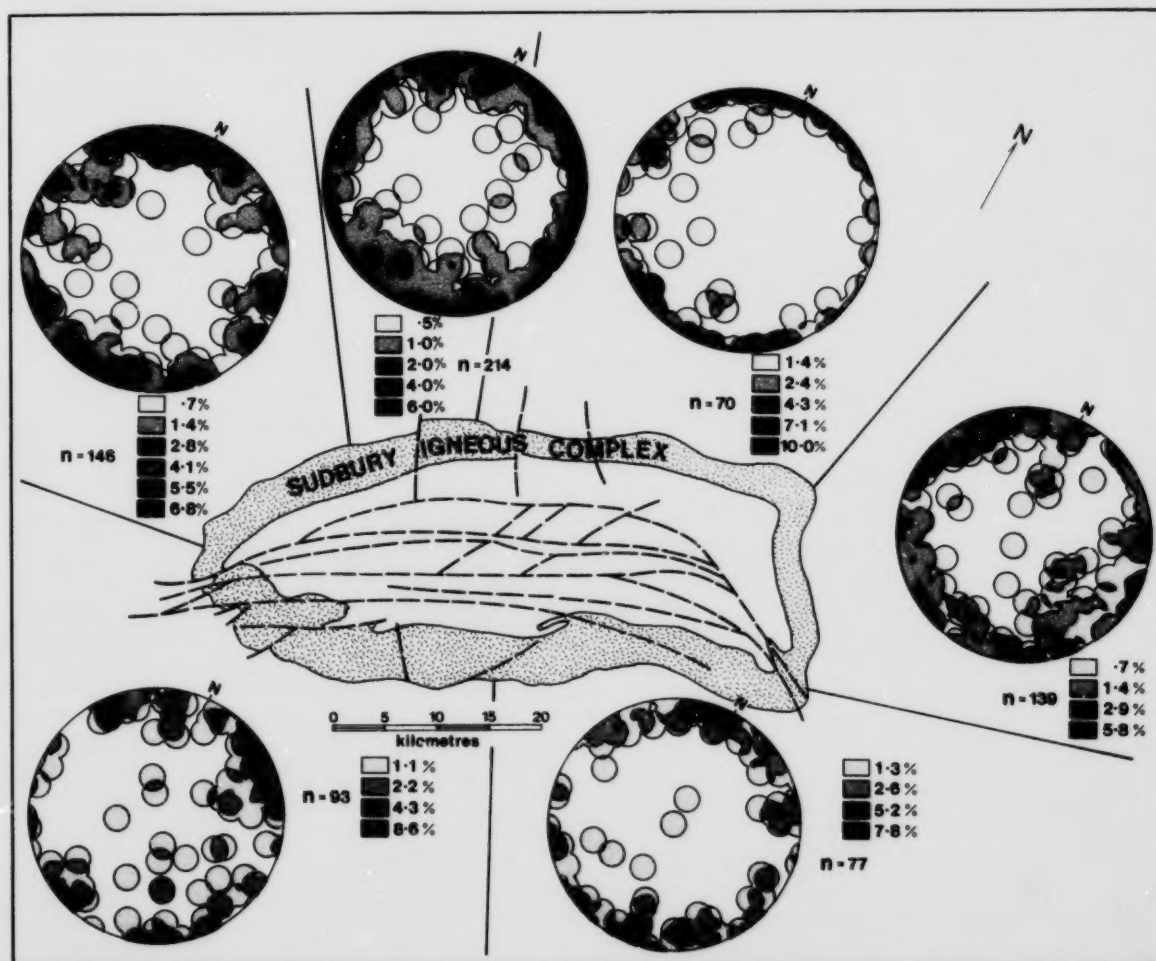


Figure 6.7. Orientation of Sudbury Breccia dikes.

were observed in the small apophysis Y that forms a right angle with dike XX. Photos 6.9 to 6.11 show Sudbury Breccia occurrences in the North and South Range Footwalls.

The size of the fragments in the breccias depends on the size of the breccia bodies. For example, large fragments, in general, are found in large breccia bodies, and small fragments in small bodies. Fragments up to 10 m in diameter are not uncommon in the larger bodies. Speers (1957) reported fragments up to 120 m long, and Yates (1948) described a 275 by 800 m large fragment near the Stobie Mine. Most fragments are rounded or subrounded, the very small rock and mineral fragments, however, are subangular to angular.

The fragments, in general, are of the same rock type as the host rock. Exotic fragments, however, are common as well. These may be derived from rocks nearby, or sources not exposed on the surface. In the areas north of the Sudbury Igneous Complex which are underlain mainly by granitic rocks, gabbroic fragments and diabase clasts are very common within the breccias, even though neither gabbro nor diabase outcrop nearby. In Rhodes Township, approximately 50 km northwest of Sudbury, Dressler (1980) observed quartz sandstone clasts of the Lorrain Formation in a

Sudbury Breccia body within Archean metavolcanic rocks. The closest outcrops of Lorrain Formation sandstone are more than 200 m away from the breccia body, and are at a slightly higher elevation. Small breccia bodies and dikes contain proportionally fewer visible fragments than large ones. Many breccia dikes and seams contain either few fragments or none. Vesicles up to 1.5 cm in diameter have been observed in the breccia matrix by the author 1.9 km east-northeast of the southwestern corner of Trill Township.

In a few thin sections, small, angular, shard-like, in places plastically deformed fragments were observed that exhibit schlieren-type flow lines (Photo 6.12). Such fragments possibly represent recrystallized glass incorporated into the breccia matrix. The glass may have originated in the same breccia body, possibly during the initial phase of breccia formation.

In hand specimen, the Sudbury Breccia matrix is commonly grey, dark grey, or black (massive breccia of Peredery and Morrison, Chapter 22, this volume). In quartz sandstones, arkoses, or other light-coloured rocks, the breccia matrix is lighter coloured than in "greenstone", gabbro, or biotite-rich granite host rocks. The colour of the matrix also depends on the degree of recrystallization from contact metamorphism near the Sudbury Igneous Complex, or from regional

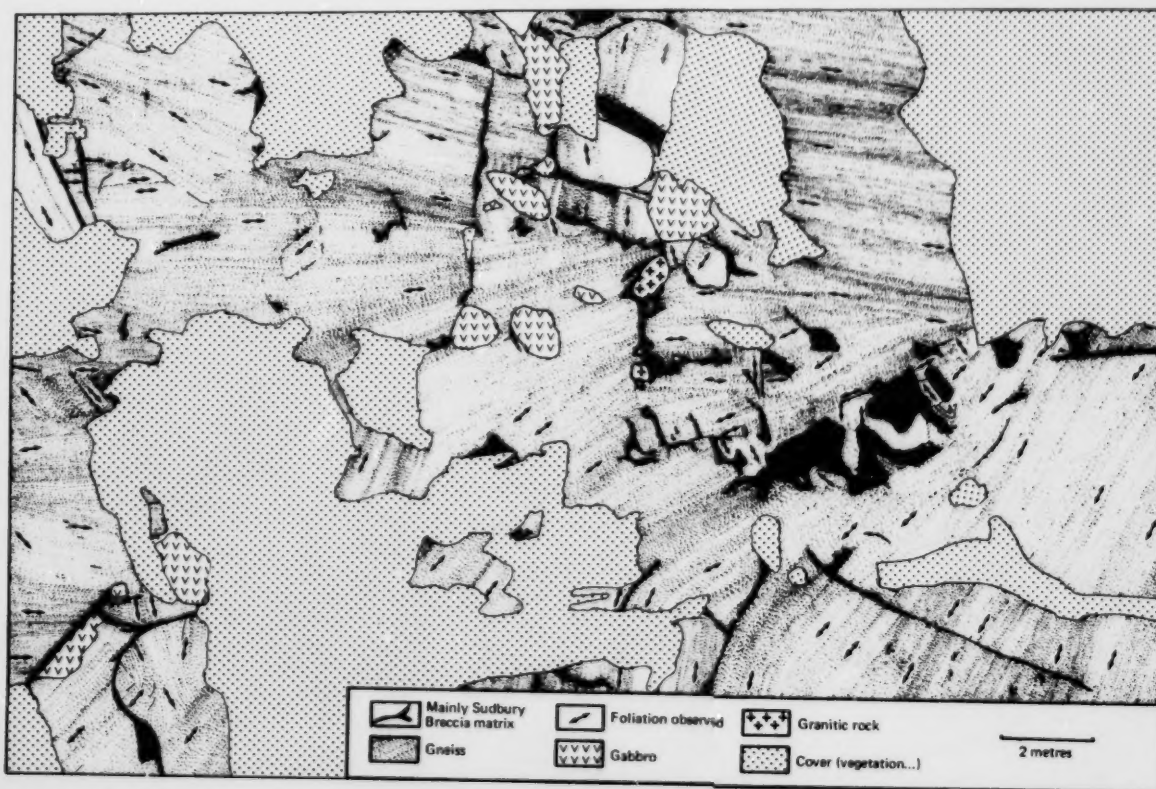
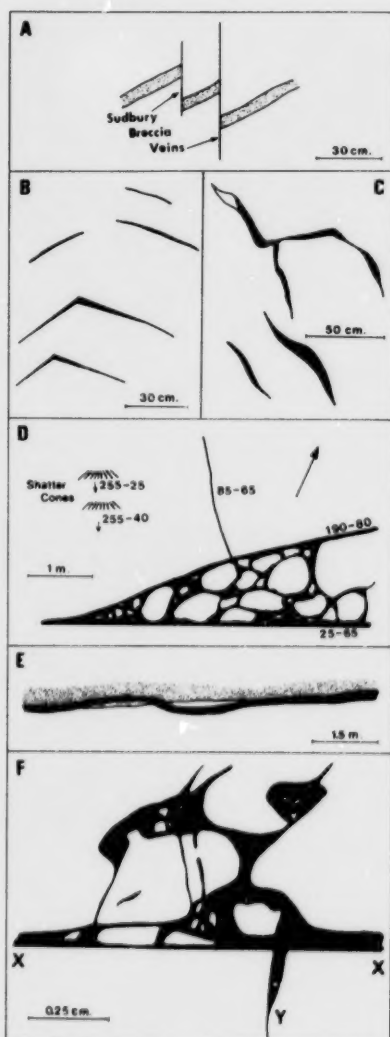


Figure 6.8. Sudbury Breccia in Levack Gneiss Complex approximately 0.5 km north of Coleman Mine, Levack Township. Note the abrupt change in the strike of the foliation in faulted gneiss blocks and the lack of breccia matrix around some fragments embedded in gneiss. Breccia dikes appear to radiate away from the main breccia body (most of the sketch) or to be approximately concentric to it.



- A – Quartz vein is offset along very thin breccia veins.
 B – Herringbone tensional fractures filled with Sudbury Breccia.
 C – Tensional fractures filled with Sudbury Breccia.
 D – “Quasi conglomerate” Sudbury Breccia body bordered by a bifurcating breccia dike; 1 offset dike subparallel to shatter cone axes (small arrows) and approximately perpendicular to breccia dike. Arrow: Direction perpendicular to Sudbury Igneous Complex contact near Hardy Mine, Levack Township, 2.4 km.
 E – Sudbury Breccia dike follows rock contact.
 F – Cataclastic flow and deformation of fragments within dike XX indicating shearing movement parallel to XX. No cataclastic flow in apophysis Y. The breccia matrix above XX appears to be squeezed from the shear zone XX into the host rock. Host rock and large fragments are diabase, small fragments are granitic rocks.

Figure 6.9. Sudbury Breccia. Examples from the North Range Footwall.

Black on sketches is breccia matrix.

A–Quartz vein is offset along very thin breccia veins.

B–Herringbone tensional fractures filled with Sudbury Breccia.

C–Tensional fractures filled with Sudbury Breccia.

D–“Quasi conglomerate” Sudbury Breccia body bordered by a bifurcating breccia dike; 1 offset dike subparallel to shatter cone axes (small arrows) and approximately perpendicular to breccia dike. Arrow: Direction perpendicular to Sudbury Igneous Complex contact near Hardy Mine, Levack Township, 2.4 km away.

E–Sudbury Breccia dike follows rock contact.

F–Cataclastic flow and deformation of clasts within dike XX indicating shearing movement parallel to XX. No cataclastic flow in apophysis Y. The breccia matrix above XX appears to be squeezed from the shear zone XX into the host rock. Host rock and large fragments are diabase, small fragments are granitic rocks.

metamorphism around the Complex. The contact metamorphosed matrix is somewhat lighter coloured than unmetamorphosed matrices due to the growth of fine-grained plagioclase within it. Greenschist facies rank regional metamorphism commonly has lead to growth of biotite in the matrix, thus causing darker colour shades.

The contacts between matrix and host rock or fragments are sharp (Photo 6.13). Very small matrix apophyses are seen to intrude fractures in Footwall rocks and fragments. In thin section, the apophyses can be seen to form fine seams branching off from the main matrix body. Cataclastic flow structures (flow banded breccia of Peredery and Morrison, Chapter 22, this volume) in the matrix were observed around fragments, or parallel to contacts with the host rocks. These flow structures are more common in the South Range than in the North Range (W.V. Peredery, Staff Geologist, Inco Limited, personal communication, 1983), and indicate that Archean high metamorphic rank rocks and igneous bedrock (North Range) reacted in a different manner to the breccia-forming process than did the South Range lower metamorphic rank rocks and possibly less competent Proterozoic metasedimentary and metavolcanic rocks.

The most common breccia matrix consists of a microscopic and submicroscopic rock and mineral flour. The lithologies that form the dominant mineral and rock fragments in the breccia are the same as the adjacent host rock. Most small fragments are angular to subrounded in shape. Quartz, when not recrystallized, has a wavy extinction, and in a few places, exhibits diaplectic planar features. The polysynthetic twinning of plagioclase fragments commonly is distorted. Speers (1957) described a deformed plagioclase fragment, parts of which appeared isotropic under crossed nicols. This isotropization is possibly diaplectic in origin. Fine, recrystallized chlorite, biotite, and epidote group minerals can also be seen in the matrix, especially in breccias of the South Range Footwall where, in places, regional metamorphism reached amphibolite facies rank. Most of the matrix material in weakly recrystallized breccias, however, is too fine grained to be resolved under the microscope.

Vesicular (Photo 6.14) and non vesicular, recrystallized melt matrices (igneous) are not common and were observed by the author only at localities close to the North Range Sudbury Igneous Complex, outside the zone of contact-metamorphic plagioclase recrystallization (see Figure 6.19). In a vesicular breccia in

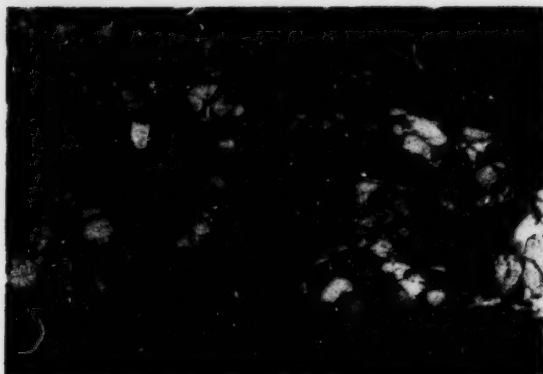


Photo 6.9. Sudbury Breccia in rocks of the Cobalt Group. (Outer zone of strong brecciation). West shore of Bassfin Lake, Rathbun Township.

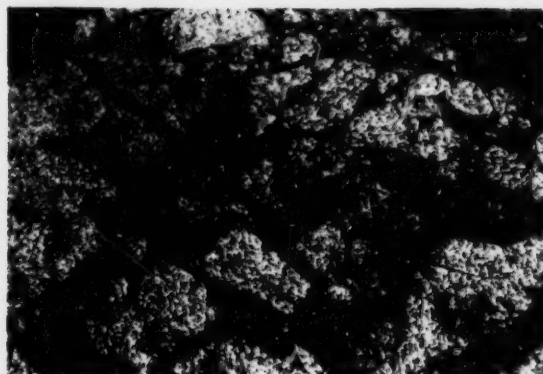


Photo 6.11. Sudbury Breccia in Creighton Pluton. East of Lockerby Mine, Graham Township. (Camera lens cap is 5 cm in diameter).

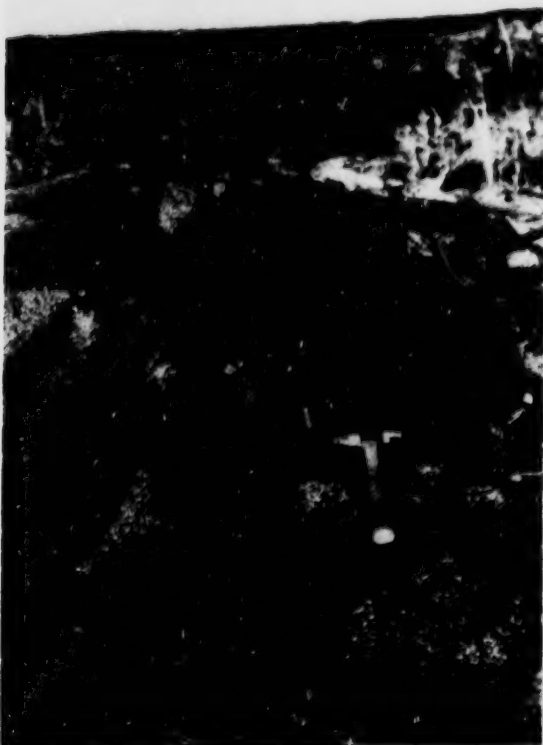


Photo 6.10. Steeply dipping Sudbury Breccia dike in Creighton Pluton. North of Clarabelle Lake, Snider Township.

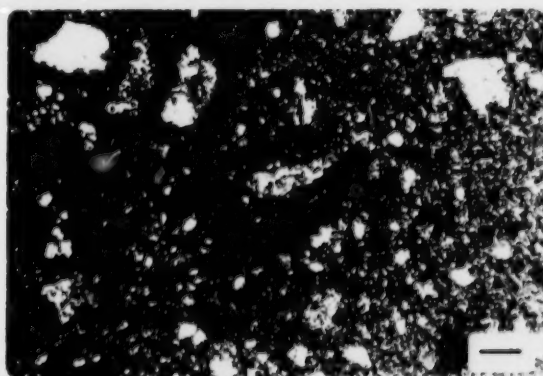


Photo 6.12. Recrystallized, deformed glass (?) fragment in Sudbury Breccia matrix. 0.9 km northwest of Sudbury Igneous Complex, 0.8 km west of northern Windy Lake plane. Polarized light. Scale 0.2 mm.

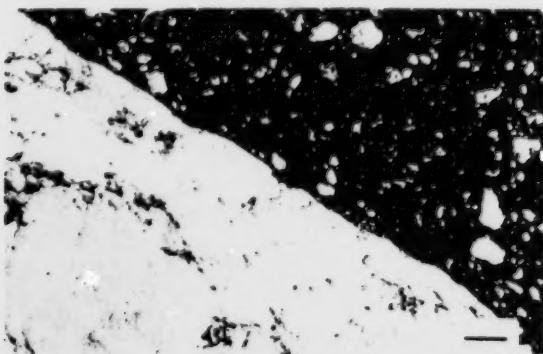


Photo 6.13. Contact of Sudbury Breccia with granitic host rock. 0.9 km northwest of Sudbury Igneous Complex, 0.8 km west of northern Windy Lake. Scale 0.3 mm.

Trill Township, the vesicles make up approximately 20% of the matrix. The remainder of the vesicular matrix is very fine grained, rich in iron-oxide, and includes many angular to subrounded fragments of quartz and plagioclase. The filled vesicles are spherical or slightly elongated and filled with calcite and actinolite; epidote and actinolite; quartz, epidote, and

actinolite; or chlorite, calcite, and actinolite. Very fine grained plagioclase microlites can be recognized within the vesicular matrix, and indicate the rock

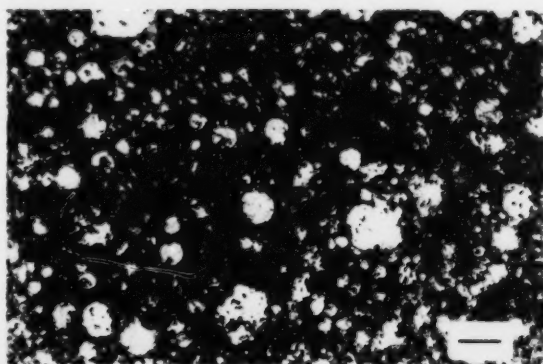


Photo 6.14. Filled vesicles in matrix of Sudbury Breccia. 0.8 km west of Sudbury Igneous Complex, 0.4 km north of southern boundary of Trill Township. Scale 0.45 mm.

formed by rapid crystallization from a melt. Similar tiny plagioclase crystals were also observed in a few thin sections of unvesiculated Sudbury Breccia matrix. In 1 thin section, the arrangement of plagioclase laths is spherulitic, suggesting either recrystallization of a glass, or primary spherulitic crystallization from a melt¹.

In a few places, Sudbury Breccia bodies exhibit evidence of more than 1 episode of brecciation. Photo 6.15, for instance, shows a Sudbury Breccia fragment imbedded in flow-textured Sudbury Breccia from the South Range. In Photo 6.16, 2 differently coloured and textured breccia matrices can be seen in sharp contact with one another.

CHEMISTRY

Speers (1957) analyzed 6 matrix-host rock pairs and concluded that "the chemical composition of the breccia matrices reflects the composition of the host rock and also indicates that foreign material has been mixed with material derived from the host rocks".

Card (1978a, p.193), from a similar study, concluded that the bulk chemical composition of the matrix materials corresponds closely to the average composition of the rock fragments, thus indicating that the breccias were formed primarily by an *in situ* milling process. Apparently, the only significant additions were water and carbon.

¹It is noteworthy that the melt matrices and also the small fragments of recrystallized glass described above, appear to be derived from the surrounding country rocks, probably by frictional heat during the generation of finely comminuted material. In the Ries (Germany) and Rochechouart (France) impact craters, dike melts are chemically associated with the impact melts (F. Hörz, Experimental Planetology Branch, NASA Johnson Space Centre, Houston, personal communication, 1983).



Photo 6.15. Sudbury Breccia fragment in Sudbury Breccia 0.8 km south of Whitson Lake, 0.7 km east of Highway 69 Blezard Township.

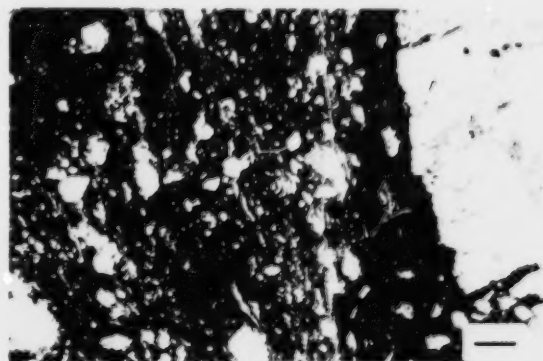


Photo 6.16. Sudbury Breccia. Dark grey to black matrix and a second, younger, lighter grey matrix. North Range Footwall. (Thin section courtesy of T.L. Muir). Scale 1 mm.

In a recent paper, Dupuis *et al.* (1982) published results of a chemical investigation of Sudbury Breccias exposed along a contact between a Nipissing gabbro body and Mississagi Formation quartz sandstone and arkose. These authors claimed that "although the gross compositions of matrix materials can be accounted for by a mixing of comminuted host gabbro

CHAPTER 6

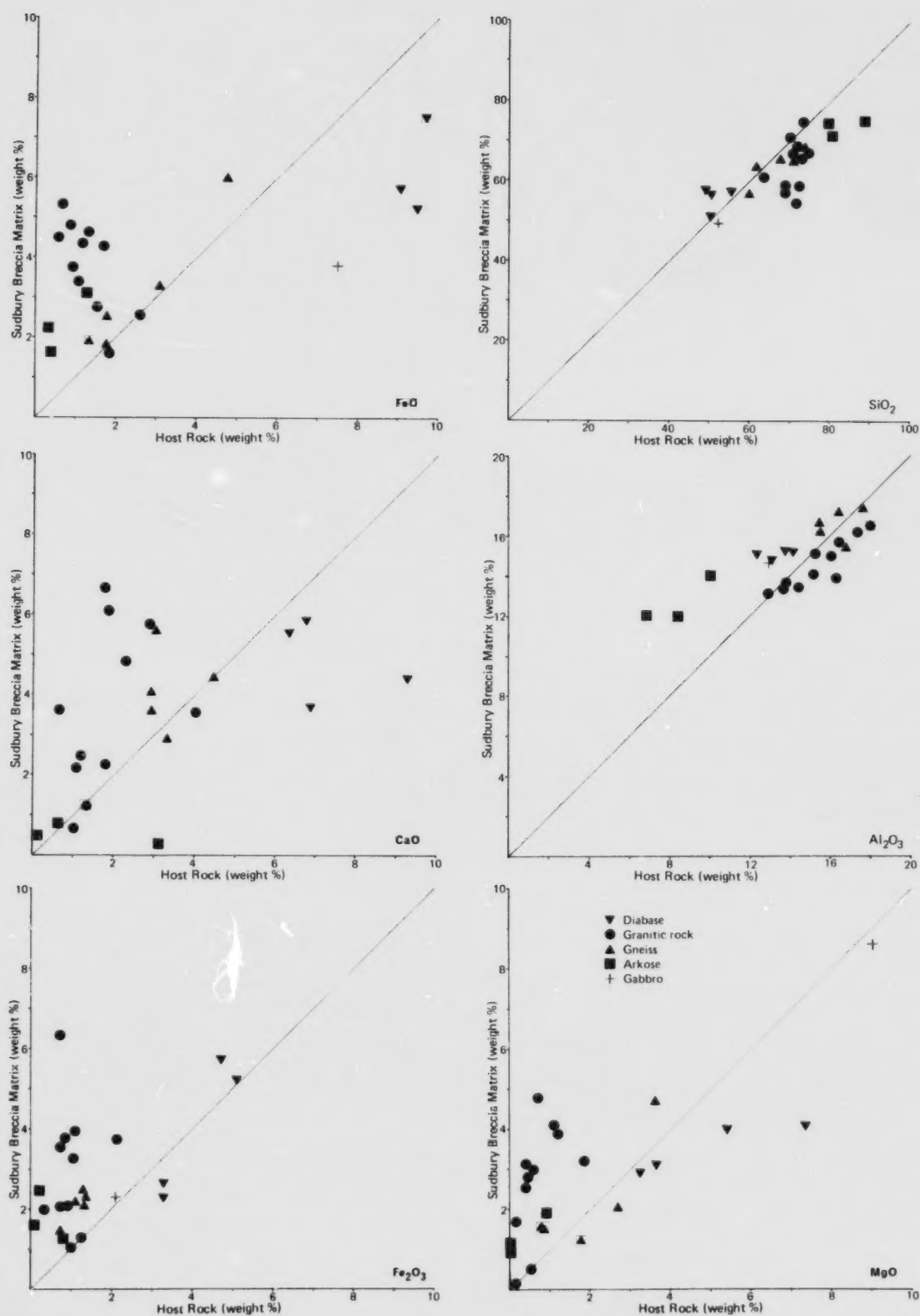


Figure 6.10. Sudbury Breccia matrix vs. host rock, major element chemistry.

TABLE 6.2A: CHEMICAL ANALYSES COMPARING HOST ROCK AND SUBBURY BRECCIA MATRIX COMPOSITIONS (COMPARE WITH FIGURE 6.10)

SAMPLE NUMBER	GRANITE HOSTROCK 03-1-15-D	SUBBURY BRECCIA 03-1-15-A	GRANITE HOSTROCK 80BOD-9011	SUBBURY BRECCIA 80BOD-9011	GRANITE HOSTROCK 80BOD-9012	SUBBURY BRECCIA 80BOD-9012	GRANITE HOSTROCK 80BOD-9015	SUBBURY BRECCIA 80BOD-9015	GRANITE HOSTROCK 80BOD-1812	SUBBURY BRECCIA 80BOD-1812	GRANITE HOSTROCK 80BOD-2915	SUBBURY BRECCIA 80BOD-2915
SiO ₂	68.20	58.40	63.90	60.70	72.10	58.40	69.10	57.00	71.50	54.40	72.40	60.60
Al ₂ O ₃	16.40	13.80	18.00	16.50	16.50	15.70	17.50	16.10	16.10	15.00	15.30	15.10
Fe ₂ O ₃	0.78	3.53	2.14	3.72	0.90	3.73	1.16	3.94	0.73	6.36	0.37	1.94
FeO	1.16	4.33	1.54	2.75	0.57	4.45	1.30	4.62	0.65	5.35	0.89	4.78
MgO	1.25	3.90	1.90	3.20	0.75	4.82	1.11	4.10	0.51	2.79	0.45	3.13
CaO	2.91	5.79	4.03	5.55	1.82	6.68	2.36	4.85	1.89	6.11	0.66	3.63
Na ₂ O	4.97	3.60	4.23	3.99	4.29	3.36	4.31	4.59	5.45	4.34	4.61	5.44
K ₂ O	2.08	3.23	1.58	1.32	1.89	0.95	1.54	1.48	1.51	1.49	4.09	1.66
TiO ₂	0.41	1.24	0.80	0.95	0.31	0.86	0.64	1.32	0.36	1.94	0.28	1.04
P ₂ O ₅	0.13	0.17	0.17	0.25	0.00	0.16	0.06	0.14	0.04	0.35	0.07	0.18
MnO	0.03	0.11	0.04	0.07	0.02	0.09	0.02	0.09	0.02	0.11	0.02	0.90
CO ₂	0.11	0.30	0.12	0.12	0.10	0.13	0.10	0.15	0.07	0.80	0.32	0.25
S	0.02	0.03	0.03	0.12	0.01	0.08	0.01	0.02	0.01	0.23	0.01	0.03
H ₂ O ⁺	0.30	0.46	0.63	0.66	0.31	0.69	0.61	0.40	0.23	0.33	0.23	1.24
H ₂ O ⁻	0.20	0.34	0.48	0.45	0.49	0.43	0.24	0.71	0.44	0.55	0.46	0.75
L.O.I.	1.00	0.90	1.4	1.2	1.2	1.3	1.3	1.1	0.80	0.80	0.80	1.50
TOTAL	98.95	99.29	99.6	100.3	100.0	100.5	100.1	99.5	99.51	99.43	100.16	99.86

SAMPLE NUMBER	GRANITE HOSTROCK 80BOD3511	SUBBURY BRECCIA 80BOD-9008	GRANITE HOSTROCK 82BOD-1011	SUBBURY BRECCIA 82BOD-1011	GRANITE HOSTROCK 82BOD-1017	SUBBURY BRECCIA 82BOD-1017	GRANITE HOSTROCK 82BOD-1019	SUBBURY BRECCIA 82BOD-1019	GRANITE HOSTROCK 82BOD-1307	SUBBURY BRECCIA 82BOD-1307	GRANITE HOSTROCK 01-1-24-A	SUBBURY BRECCIA 01-1-24-B
SiO ₂	70.90	66.30	73.50	66.30	73.30	74.30	70.10	70.60	72.10	68.50	67.30	65.20
Al ₂ O ₃	15.20	14.00	13.80	13.70	13.00	13.10	13.70	13.40	14.40	13.40	17.60	17.30
Fe ₂ O ₃	1.05	3.31	0.93	2.04	1.05	1.08	1.27	1.27	0.74	2.03	0.78	1.46
FeO	0.97	3.73	1.69	4.27	1.85	1.53	2.66	2.58	1.05	3.39	1.33	1.83
MgO	0.84	2.96	0.18	2.96	0.17	1.72	0.61	0.54	0.42	2.55	0.79	1.53
CaO	1.03	0.65	1.20	2.52	1.33	1.26	1.82	2.29	1.11	2.21	3.30	2.89
Na ₂ O	4.03	4.42	2.19	2.66	2.31	2.24	2.65	2.88	3.88	3.82	5.11	6.27
K ₂ O	5.30	5.31	5.71	4.14	5.37	5.52	4.66	4.61	4.91	1.58	1.31	1.71
TiO ₂	0.40	0.54	0.30	0.75	0.52	0.30	0.75	0.58	0.31	0.56	0.49	0.60
P ₂ O ₅	0.17	0.08	0.03	0.04	0.03	0.02	0.04	0.05	0.02	0.00	0.12	0.15
MnO	0.01	0.04	0.03	0.08	0.03	0.04	0.05	0.06	0.02	0.07	0.02	0.04
CO ₂	0.17	0.19	0.06	0.10	0.22	0.19	0.27	0.35	0.05	0.05	0.15	0.18
S	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
H ₂ O ⁺	0.23	1.52	0.39	0.91	0.33	0.29	0.63	0.30	0.52	1.51	0.41	0.76
H ₂ O ⁻	0.39	0.73	0.06	0.06	0.03	0.04	0.03	0.09	0.04	0.04	0.26	0.38
L.O.I.	0.60	2.50	0.60	1.10	0.80	0.7	1.20	1.00	1.00	1.80	0.90	1.20
TOTAL	100.50	99.82	100.0	99.4	99.50	100.0	99.20	99.6	99.5	99.70	98.98	100.31

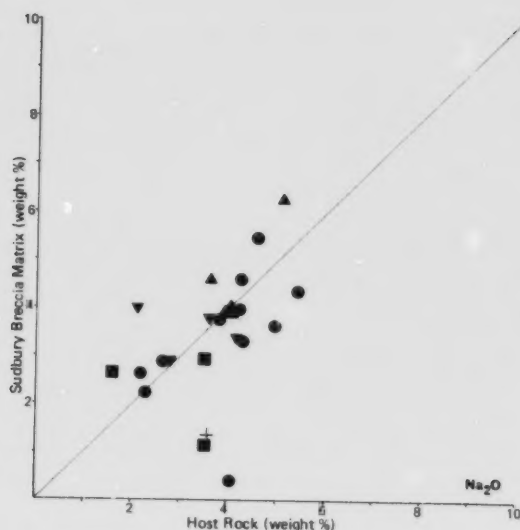
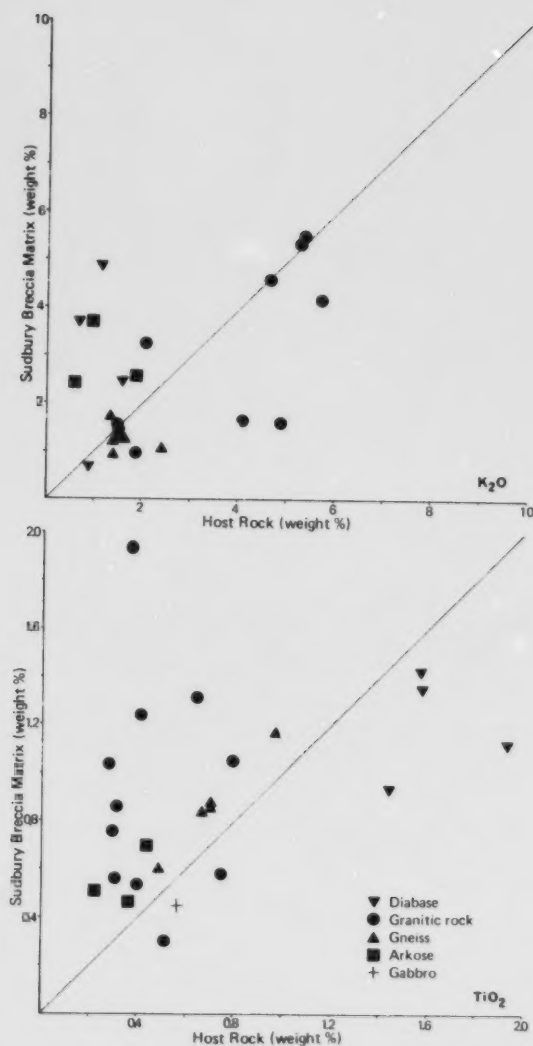


Figure 6.10. Sudbury Breccia matrix vs. host rock, major element chemistry.

and quartzite, enrichments in K_2O , Rb, TiO_2 , Zr, Y, Ba, Sr, and P_2O_5 also occur".

In Table 6.2, the compositions of 24 matrix-host rock pairs are listed. Table 6.3 shows chemical analyses of rocks taken from within the area investigated by Dupuis *et al.* (1982). Tables 6.4 and 6.5 list analyses of rocks from 2 other large breccia bodies sampled in detail. All these chemical data (Tables 6.2 to 6.5) are plotted in Figures 6.10 to 6.13. The locations of the chemically studied breccia bodies are listed in the tables.

In Figure 6.10 (Table 6.2), the major elements of host rocks are compared to the breccia matrices. In general, no definite SiO_2 loss or enrichment trend for all matrices can be recognized by comparing these analyses. In detail, however, some specific changes are quite evident. The SiO_2 content of matrices is higher than in the host diabase, and the SiO_2 content of matrices is lower than in host arkoses and most granitic rocks. Analyses of Al_2O_3 behave similarly, but the arkoses and most of the gneisses plot above the mixing

line. The figure shows iron-enrichments for almost all matrices except for the ones hosted by mafic rocks. The same is valid for the MgO and CaO diagrams. Analyses for Na_2O and K_2O , which are mobile components, show that no clear trends of enrichments or losses of these components can be detected. No consistent variation exists among analyzed host rock-breccia matrix pairs.

Thus, Figure 6.10 indicates clearly that the chemical characteristics of the breccia matrices can be explained by assuming that the breccia-forming process not only affected the immediate host rocks, but also some other, "foreign" material. Breccia matrices in mafic host rocks such as diabase probably incorporated some granitic or arkosic material, or at least, rocks closer to the felsic end of the chemical spectrum. On the other hand, breccia matrices in arkosic host rocks are enriched in elements that are more common in more mafic rocks, and thereby suggest the incorporation of such rocks during the breccia-forming process.

TABLE 6.28: CHEMICAL ANALYSES COMPARING HOST ROCK AND SUDBURY BRECCIA MATRIX COMPOSITIONS (COMPARE WITH FIGURE 6.10)

SAMPLE NUMBER	GNEISS HOSTROCK 80BOD-9018	SUDBURY BRECCIA 80BOD-9017	GNEISS HOSTROCK 80BOD-9021	SUDBURY BRECCIA 80BOD-9019	GNEISS HOSTROCK 80BOD-9021	SUDBURY BRECCIA 80BOD-9020	GNEISS HOSTROCK 80BOD-26-4	SUDBURY BRECCIA 80BOD-9001	DIABASE HOSTROCK 03-1-15-C	SUDBURY BRECCIA 03-1-15-B	DIABASE HOSTROCK 80BOD-9003	SUDBURY BRECCIA 80BOD-9004
SiO ₂	64.00	63.70	70.50	65.10	70.50	68.00	59.80	56.70	55.30	56.90	50.60	51.30
Al ₂ O ₃	16.40	17.10	15.50	16.60	15.50	16.10	16.80	15.40	13.10	14.80	14.10	15.20
Fe ₂ O ₃	1.31	2.49	1.36	2.30	1.36	2.07	1.12	2.21	5.10	5.22	4.70	5.74
FeO	3.06	3.24	1.78	2.51	1.78	1.78	4.78	5.99	9.07	5.74	9.64	7.53
MgO	2.77	1.98	0.87	1.51	0.87	1.23	3.64	4.70	3.27	2.92	3.67	3.08
CaO	4.50	4.40	2.92	4.07	2.92	3.65	3.02	5.58	6.87	5.83	6.35	5.54
Na ₂ O	3.96	3.85	4.08	3.93	4.08	4.04	3.62	4.59	2.80	2.92	4.14	3.39
K ₂ O	1.61	1.25	1.38	0.93	1.38	1.20	2.42	1.07	1.58	2.46	0.67	3.70
TiO ₂	0.66	0.83	0.70	0.88	0.70	0.86	0.97	1.1	1.58	1.35	2.39	2.21
P ₂ O ₅	0.06	0.13	0.08	0.13	0.08	0.10	0.21	0.25	0.22	0.21	0.42	0.37
MnO	0.07	0.08	0.06	0.06	0.06	0.05	0.06	0.08	0.18	0.11	0.20	0.13
CO ₂	0.13	0.08	0.09	0.18	0.09	0.27	0.10	0.14	0.12	0.11	0.11	0.21
S	0.01	0.08	0.01	0.04	0.01	0.03	0.20	0.24	0.15	0.05	0.03	0.80
H ₂ O ⁺	0.67	1.08	0.09	0.39	0.09	0.55	0.88	1.33	0.36	0.42	1.49	0.87
H ₂ O ⁻	0.46	0.39	0.50	0.40	0.50	0.52	0.61	0.62	0.32	0.28	0.65	0.59
L.O.I.	1.3	1.2	0.8	1.5	0.8	1.5	1.20	1.70	0.40	0.50	1.20	0.90
TOTAL	99.7	100.6	99.9	99.0	99.9	100.4	98.23	100.07	99.93	99.53	99.16	99.94

SAMPLE NUMBER	DIABASE HOSTROCK 80BOD-9006	SUDBURY BRECCIA 80BOD-9007	DIABASE HOSTROCK 82BOD-3817	SUDBURY BRECCIA 80BOD-9009	ARKOSE HOSTROCK 81BOD-5905	SUDBURY BRECCIA 81BOD-9008	ARKOSE HOSTROCK 81BOD-9009	SUDBURY BRECCIA 81BOD-5908	ARKOSE HOSTROCK 81BOD-9011	SUDBURY BRECCIA 81BOD-6201	ARKOSE HOSTROCK 82BOD-0409	SUDBURY BRECCIA 82BOD-0408
SiO ₂	48.80	58.20	50.20	56.80	79.80	74.40	89.00	75.00	80.20	71.30	52.10	49.40
Al ₂ O ₃	13.80	15.20	12.30	15.10	8.45	12.00	6.97	12.00	10.10	14.00	12.90	14.60
Fe ₂ O ₃	3.30	2.28	3.30	2.64	0.21	2.45	0.00	1.63	0.82	1.31	2.09	2.31
FeO	10.90	6.89	9.48	5.27	0.40	1.61	0.32	2.18	1.29	3.14	7.50	5.80
MgO	5.40	3.99	7.34	4.04	0.03	0.94	0.00	1.12	0.95	1.88	9.04	8.60
CaO	9.29	4.39	6.91	3.69	3.16	0.32	0.13	0.50	0.65	0.82	7.92	12.00
Na ₂ O	2.12	4.05	3.60	3.82	3.50	2.93	1.60	2.67	3.48	1.16	3.57	1.37
K ₂ O	0.88	0.65	1.11	4.88	0.60	2.44	1.90	2.56	0.98	3.71	0.37	2.17
TiO ₂	1.44	0.93	1.93	1.12	0.37	0.47	0.23	0.51	0.54	0.70	0.57	0.45
P ₂ O ₅	0.13	0.12	0.31	0.25	0.02	0.04	0.02	0.02	0.00	0.02	0.04	0.06
MnO	0.21	0.12	0.15	0.09	0.06	0.03	0.01	0.04	0.02	0.03	0.21	0.24
CO ₂	0.18	0.12	0.11	0.24	2.48	0.14	0.05	0.16	0.10	0.12	0.28	0.22
S	0.04	0.05	0.04	0.12	0.02	0.03	0.01	0.02	0.03	0.01	0.01	0.13
H ₂ O ⁺	1.12	1.57	1.31	0.80	0.30	1.26	0.29	1.26	1.02	1.82	2.13	1.74
H ₂ O ⁻	0.55	0.57	0.40	0.40	0.06	0.04	0.03	0.04	0.06	0.04	0.19	0.15
L.O.I.	1.5	1.9	1.40	1.30	2.1	1.3	0.3	1.3	0.5	1.6	2.3	1.9
TOTAL	98.2	99.2	98.49	99.26	99.3	99.1	100.3	99.7	100.2	100.2	98.8	99.1

TABLE 6.3: CHEMICAL ANALYSES COMPARING HOST ROCK AND FRAGMENT COMPOSITIONS WITH COMPOSITIONS OF SUDBURY BRECCIA MATRIX. ALL SPECIMENS FROM ONE OUTCROP AREA; LAURENTIAN UNIVERSITY CAMPUS, SUDBURY (COMPARE WITH FIGURE 6.11)

82BOD: SAMPLE NUMBER	SUDBURY BRECCIA MATRIX											NIPISSING GABBRO FRAGMENTS						
	4901	4902	4903	4908	4912	4913	4914	4915	4916	MEAN (n = 9)	δ	4907	4910	4918	4921	4923	4925	
SiO ₂	63.7	65.7	67.7	80.1	61.8	59.5	69.2	69.2	67.9	67.2	5.9	50.6	50.6	50.1	50.3	50.5	50.6	
Al ₂ O ₃	10.4	10.1	11.3	9.99	11.2	10.7	11.9	10.9	9.38	10.65	0.77	7.44	8.61	7.25	11.2	11.8	7.03	
Fe ₂ O ₃	1.44	1.93	1.15	0.76	1.99	1.32	0.72	0.93	1.44	1.30	0.46	1.94	2.31	2.31	1.51	1.06	1.44	
FeO	4.84	5.00	5.16	1.53	4.76	6.21	3.55	3.71	4.59	4.37	1.32	9.11	8.22	8.46	7.25	7.25	8.95	
MgO	8.08	7.31	5.69	1.94	8.38	9.57	4.96	5.36	7.50	6.53	2.30	16.2	14.5	16.5	12.9	12.8	16.8	
CaO	5.82	4.35	1.35	0.32	4.39	6.69	2.85	4.05	4.56	3.82	2.02	8.85	9.19	9.53	11.1	10.9	9.67	
Na ₂ O	2.66	1.67	1.18	3.24	1.89	1.50	2.70	2.18	1.79	2.09	0.66	0.34	0.38	0.66	0.73	0.88	0.38	
K ₂ O	0.42	1.48	1.25	0.18	0.82	0.12	0.29	0.72	0.45	0.64	0.47	0.73	1.14	0.23	0.48	0.42	0.30	
TiO ₂	0.82	0.68	0.75	0.48	0.52	0.59	0.56	0.52	0.46	0.00	0.13	0.54	0.60	0.54	0.56	0.52	0.49	
P ₂ O ₅	0.02	0.01	0.04	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.009	0.01	0.02	0.01	0.01	0.02	0.02	
MnO	0.10	0.08	0.07	0.02	0.08	0.11	0.06	0.06	0.09	0.07	0.026	0.19	0.17	0.19	0.16	0.15	0.19	
CO ₂	0.06	0.34	0.20	0.03	0.72	0.07	0.12	0.04	0.04	0.18	0.23	0.07	0.16	0.11	0.27	0.23	0.08	
S	0.02	0.09	0.06	0.04	0.23	0.06	0.06	0.13	0.15	0.09	0.06	0.02	0.07	0.02	0.04	0.03	0.02	
H ₂ O ⁺	1.81	2.07	2.65	1.32	2.21	2.52	2.02	1.38	1.69	1.96	0.46	3.42	3.48	2.75	2.42	2.43	2.95	
H ₂ O ⁻	0.16	0.17	0.10	0.10	0.09	0.08	0.07	0.03	0.08	0.10	0.04	0.18	0.10	0.11	0.08	0.07	0.17	
L.O.I.	1.8	2.0	2.5	1.0	2.9	1.9	1.7	0.7	1.0			3.1	2.6	2.4	1.8	1.8	3.3	
TOTAL	100.4	100.9	98.6	100.0	99.1	99.0	98.8	99.2	100.1			99.6	99.7	96.8	99.0	99.2	99.1	

82BOD: SAMPLE NUMBER	NIPISSING GABBRO HOSTROCK			FINE GABBRO FRAG- MENT			ARKOSE HOSTROCK			ARKOSE FRAGMENTS			WACKIE FRAGMENTS		
	4919	4929	4911	4911	4926	4927	4928	4909	4917	4920	4922	4924	4904	4905	4906
SiO ₂	50.4	50.7	48.4	87.2	87.2	88.1	89.1	92.2	92.1	83.8	81.9	88.8	48.9	50.5	87.1
Al ₂ O ₃	9.88	7.92	12.8	8.12	8.12	7.84	7.36	5.68	6.66	9.06	9.56	6.98	12.3	12.3	8.22
Fe ₂ O ₃	2.16	1.76	4.56	0.10	0.10	0.00	0.01	0.00	0.00	0.37	0.32	0.17	4.50	5.10	0.07
FeO	8.62	8.62	9.91	0.65	0.65	0.56	0.32	0.40	0.20	1.05	1.25	0.48	7.66	9.03	0.40
MgO	13.3	15.7	5.23	0.51	0.51	0.42	0.04	0.17	0.03	1.17	1.35	0.50	5.36	5.16	0.15
CaO	9.01	8.97	9.25	0.24	0.24	0.14	0.15	0.13	0.18	0.58	0.36	0.41	9.12	7.41	0.24
Na ₂ O	1.03	0.81	1.53	2.22	2.22	1.94	2.48	1.83	1.77	2.56	3.48	1.93	0.57	0.48	2.79
K ₂ O	0.43	0.51	1.00	0.15	0.15	0.23	0.13	0.09	0.15	0.12	0.15	0.05	3.45	4.01	0.18
TiO ₂	0.69	0.69	2.29	0.37	0.37	0.33	0.20	0.27	0.12	0.33	0.28	0.22	2.07	2.17	0.28
P ₂ O ₅	0.02	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.14	0.15	0.01
MnO	0.17	0.18	0.19	0.01	0.01	0.01	0.01	0.00	0.00	0.02	0.02	0.01	0.12	0.14	0.01
CO ₂	0.09	0.09	0.74	0.09	0.09	0.05	0.05	0.07	0.04	0.06	0.05	0.10	3.00	1.76	0.06
S	0.03	0.02	0.33	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.92	0.43	0.02
H ₂ O ⁺	2.54	3.13	2.15	0.65	0.65	0.42	0.06	0.32	0.30	0.80	0.92	0.46	2.20	2.17	0.49
H ₂ O ⁻	0.08	0.15	0.10	0.11	0.11	0.09	0.07	0.04	0.06	0.08	0.08	0.10	0.21	0.21	0.07
L.O.I.	1.7	3.3	1.8	0.7	0.7	1.0	0.8	0.2	0.1	0.6	0.9	0.4	4.6	3.3	0.1
TOTAL	98.4	99.3	96.7	100.4	100.4	100.2	100.0	101.1	101.5	100.00	99.7	100.2	100.5	100.5	100.1

TABLE 6.4: CHEMICAL ANALYSES OF SUDBURY BRECCIA. ONE OUTCROP, SOUTH-CENTRAL BASSFIN LAKE, RATHBUN TOWNSHIP (COMPARE WITH FIGURE 6.28)

SAMPLE NUMBER	SUDBURY BRECCIA MATRIX			ARKOSE HOST ROCK			ARKOSE FRAGMENTS		
	82BOD 4820	82BOD 4821	82BOD 4822	82BOD 4823	82BOD 4824	82BOD 4825	82BOD 4826	82BOD 4827	82BOD 4828
SiO ₂	77.1	76.4	73.0	81.0	86.0	85.7	63.6	63.9	72.6
Al ₂ O ₃	12.1	12.3	13.1	9.42	8.79	7.53	18.2	17.8	13.8
Fe ₂ O ₃	2.35	1.60	2.31	1.47	0.76	0.79	3.65	2.96	1.82
FeO	1.29	1.21	2.26	1.13	0.48	0.73	1.93	1.95	2.18
MgO	1.01	0.97	1.76	0.90	0.22	0.52	2.12	2.10	2.01
CaO	0.13	0.25	0.18	0.71	0.33	0.43	0.34	0.24	0.20
Na ₂ O	1.73	2.41	2.87	2.74	2.06	1.00	1.22	1.80	2.84
K ₂ O	2.74	2.77	2.50	1.21	1.39	2.09	6.03	5.42	2.53
TiO ₂	0.39	0.45	0.49	0.33	0.23	0.23	0.73	0.88	0.44
P ₂ O ₅	0.01	0.00	0.02	0.00	0.00	0.00	0.11	0.06	0.00
MnO	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01
CO ₂	0.05	0.21	0.13	0.89	0.35	0.55	0.04	0.04	0.49
S	0.04	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.01
H ₂ O ⁺	1.08	1.09	1.48	0.44	0.17	0.34	2.41	2.34	1.72
H ₂ P ⁻	0.11	0.10	0.14	0.10	0.13	0.10	0.17	0.161	0.13
L.O.I.	1.2	1.4	1.4	1.4	0.4	1.0	2.3	2.4	1.8
Total	100.2	99.7	100.3	100.4	100.8	100.0	100.6	99.6	100.8

TABLE 6.5: CHEMICAL ANALYSES OF SUDBURY BRECCIA. ONE OUTCROP, CENTRAL BASSFIN LAKE, WESTERN SHORE, RATHBUN TOWNSHIP (COMPARE WITH FIGURE 6.29)

SAMPLE NUMBER	SUDBURY BRECCIA MATRIX			ARKOSE HOST ROCK			ARKOSE FRAGMENTS			LAMINATED WACKE FRAGMENTS		
	82BOD 4811	82BOD 4812	82BOD 4813	82BOD 4808	82BOD 4809	82BOD 4810	82BOD 4814	82BOD 4815	82BOD 4816	82BOD 4817	82BOD 4818	82BOD 4819
SiO ₂	65.7	70.6	69.3	77.7	87.0	82.6	88.3	87.1	79.6	58.5	59.7	60.1
Al ₂ O ₃	16.1	14.4	14.7	11.9	8.43	9.78	7.96	8.56	11.3	19.3	18.4	18.4
Fe ₂ O ₃	3.79	2.77	2.98	1.38	0.28	0.89	0.69	0.28	1.31	4.62	5.26	4.74
FeO	2.50	1.93	2.50	1.05	0.32	0.56	0.40	0.40	1.61	3.06	2.66	2.66
MgO	2.10	1.69	2.01	0.91	0.00	0.30	0.02	0.61	1.40	2.77	2.42	2.88
CaO	0.30	0.24	0.24	0.17	0.11	0.16	0.16	0.12	0.16	0.18	0.32	0.29
Na ₂ O	1.46	2.53	3.43	2.18	1.76	3.27	2.04	2.14	3.57	0.72	1.27	1.43
K ₂ O	3.71	2.64	2.33	2.11	1.66	0.87	1.33	0.93	1.18	5.88	5.33	5.17
TiO ₂	0.69	0.55	0.60	0.32	0.09	0.35	0.20	0.15	0.21	0.84	0.82	0.86
P ₂ O ₅	0.04	0.03	0.02	0.03	0.01	0.00	0.00	0.00	0.00	0.05	0.09	0.09
MnO	0.05	0.05	0.05	0.01	0.01	0.01	0.00	0.00	0.01	0.05	0.01	0.01
CO ₂	0.13	0.11	0.07	0.11	0.05	0.07	0.10	0.04	0.03	0.05	0.04	0.06
S	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
H ₂ O ⁺	2.32	1.75	1.86	1.26	0.13	0.43	0.32	0.23	0.34	3.39	2.84	3.06
H ₂ P ⁻	0.18	0.16	0.13	0.16	0.09	0.09	0.06	0.07	0.11	0.19	0.16	0.20
L.O.I.	2.4	1.7	1.6	1.4	0.5	0.8	0.0	0.3	1.11	3.1	3.3	3.3
Total	99.6	99.5	100.3	99.3	100.0	99.3	101.1	100.0	100.9	99.6	99.4	100.0

To demonstrate this mixing process somewhat clearer, 3 larger breccia outcrops were sampled in detail. These are the one studied by Dupuis *et al.* (1982), and 2 at Bassfin Lake east of Wanapitei Lake. The chemical compositions of the host rocks, matrices, and fragments listed in Tables 6.3, 6.4, and 6.5 are plotted in Figures 6.11 to 6.13. All diagrams except for the MgO/SiO₂ plot in Figure 6.11 present clear chemical

evidence that the Sudbury Breccias were formed by an *in situ* milling process involving host rocks and fragments. The breccia compositions, in all but 1 diagram, plot between the various compositions of host rocks and fragments. The "enrichment" of the breccia matrix in K₂O and other elements observed by Dupuis *et al.* (1982), is caused by the incorporation of biotite-rich metasedimentary rocks that are not uncommon in

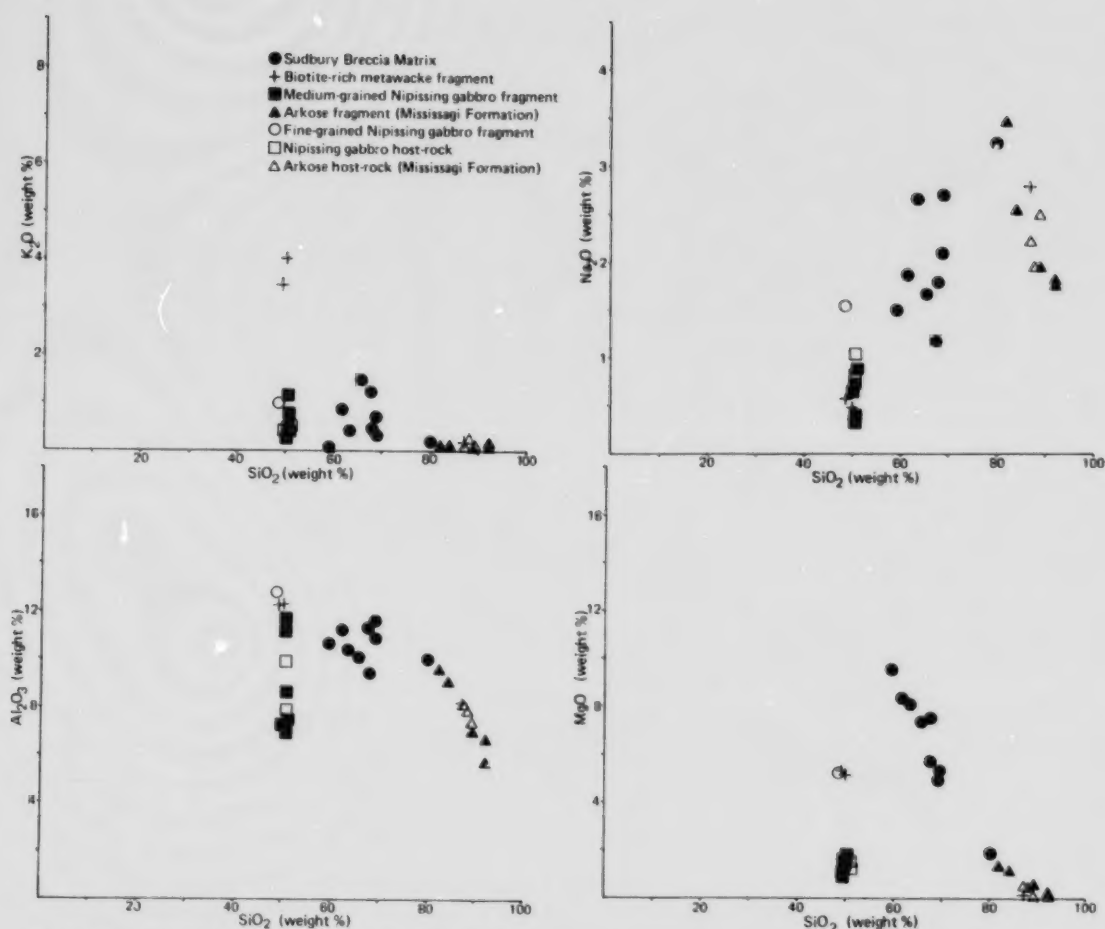


Figure 6.11. Plots of SiO_2 vs. K_2O , Na_2O , Al_2O_3 , and MgO . Sudbury Breccia, near Laurentian University Campus, McKim Township.

the Sudbury Breccia body studied near the Laurentian University Campus in Sudbury. These biotitic meta-sedimentary rocks were not detected by Dupuis *et al.* (1982)².

COMPARISON OF THE SUDBURY BRECCIA WITH BRECCIAS IN OTHER GEOLOGICAL STRUCTURES

The Sudbury Breccia has been compared with pseudotachylites (Speers 1957; Card 1978a; Dressler 1982) and other breccias that have been found in several geological structures, for instance, the Vredefort Structure in South Africa, the Ries crater in south Ger-

many, and the Manicouagan crater in Quebec. Pseudotachylites are also known to occur along faults (Philpotts 1964). A Himalayan hyalomylonite (Scott and Drever 1953), very similar to pseudotachylite, was interpreted by Masch and Preuss (1977) to be partly fused rock at the base of a huge landslide.

Many definitions and uses of the term "pseudotachylite" exist in the geological literature. Shand (1916) who introduced the term pseudotachylite for branching, dark coloured, glassy looking, dike-like rocks that resemble tachylite, and which are found in rocks of the Vredefort Structure in South Africa, came to the conclusion that "...the pseudotachylite has originated from the granite itself through melting, caused not by shearing but by shock, or alternatively, by gas-fluxing". Philpotts (1964) concluded his paper on the origin of pseudotachylites to state that such rocks were formed by frictional fusion and could be distinguished "...from similar appearing rocks of purely cataclastic origin by the presence of glass, vesicles, and microlites of intermediate to high temperature

²The MgO-enrichment in Figure 6.11 is probably metamorphic in origin. The outcrop represented by this figure is located in middle to high greenschist facies terrain. The other outcrops represented by Figures 6.12 and 6.13 are located in low greenschist facies terrain.

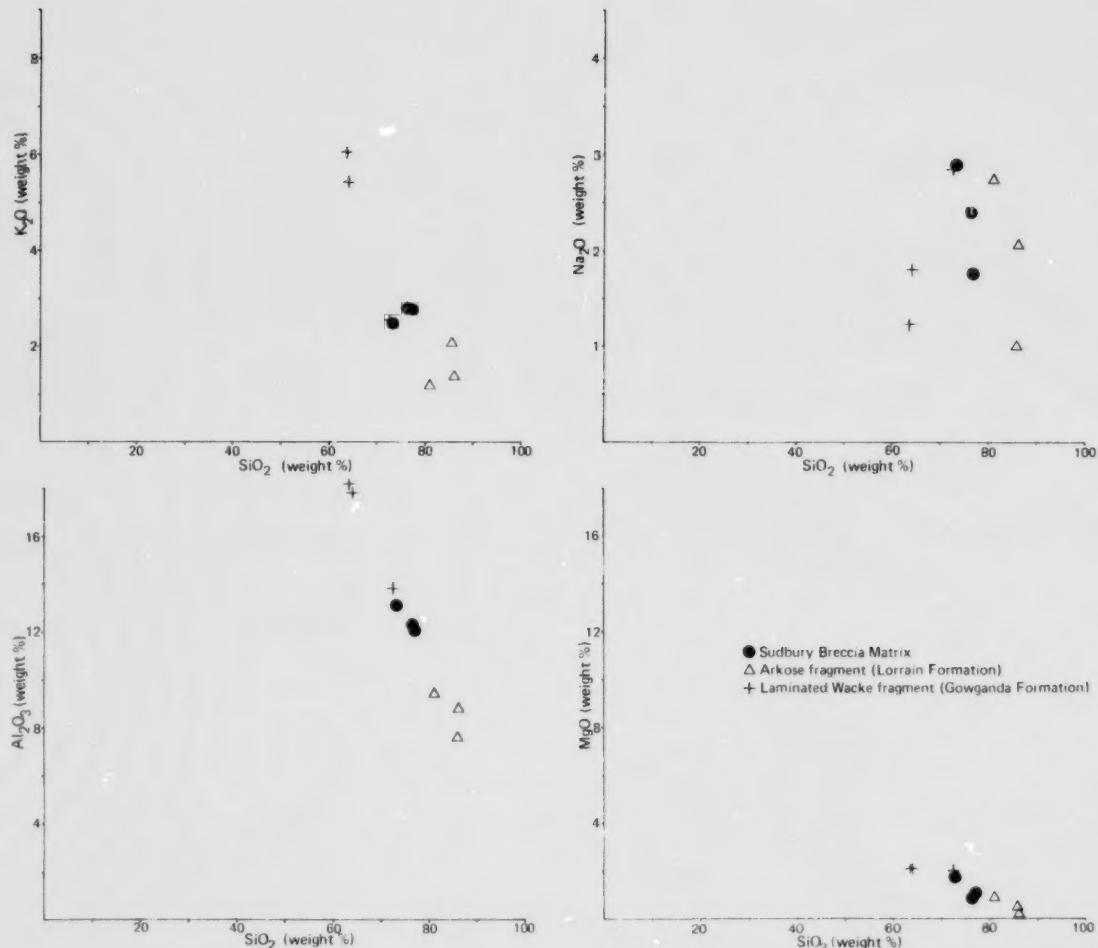


Figure 6.12. Plots of SiO₂ vs. K₂O, Na₂O, Al₂O₃, and MgO; Sudbury Breccia; south-central western shore of Bassfin Lake, Rathbun Township.

feldspars". The pseudotachylites of the South African type location, however, do not contain much clear evidence of fusion as Wilshire (1971) has shown. The only indication that the Vredefort pseudotachylites ever contained glassy material are "newly crystallized feldspar laths possibly formed by recrystallization from partly fused material" that occur in rare small pseudotachylite veins (Wilshire 1971). Higgins (1971) defined pseudotachylites to be "a glassy rock resembling tachylite, commonly of intrusive habit, and closely associated with faults or fault zones". Waters and Campbell (1935), as stated by Higgins (1971), concluded that pseudotachylite formed not by fusion, but by extreme crushing of rock material. Higgins (1971) retained the prerequisite of fusion as a distinctive property of pseudotachylite. Weiss and Wenk (1983) stated that to date no identifiable relict glass has been discovered in any pseudotachylite. These authors experimentally produced pseudotachylite-like veins during catastrophic failure of gabbroic rocks un-

der rapidly applied stresses in the 2.0 to 4.0 GPa range.

The Sudbury Breccias contain fused, recrystallized material in only a very few places. The characteristic properties of the breccias, however, are identical to those described by Wilshire (1971) from the South African type location. Therefore, the author of this chapter feels that it is justified to classify the Sudbury Breccias as pseudotachylites.

In the Ries crater in southern Germany, dike breccias occur in a few large crystalline basement rock blocks ejected from the crater during the crater forming impact event. The breccias were called "crystalline explosion breccias" in the older literature. These rocks macroscopically resemble the Sudbury Breccias (Dressler *et al.* 1969, p.222). These breccias show anastomosing veins penetrating the host rocks or form long thin dikes that, as in Figure 6.8, seem to radiate away from a more irregularly shaped breccia body. Dressler and Graup (1969) found fine, glassy pseu-

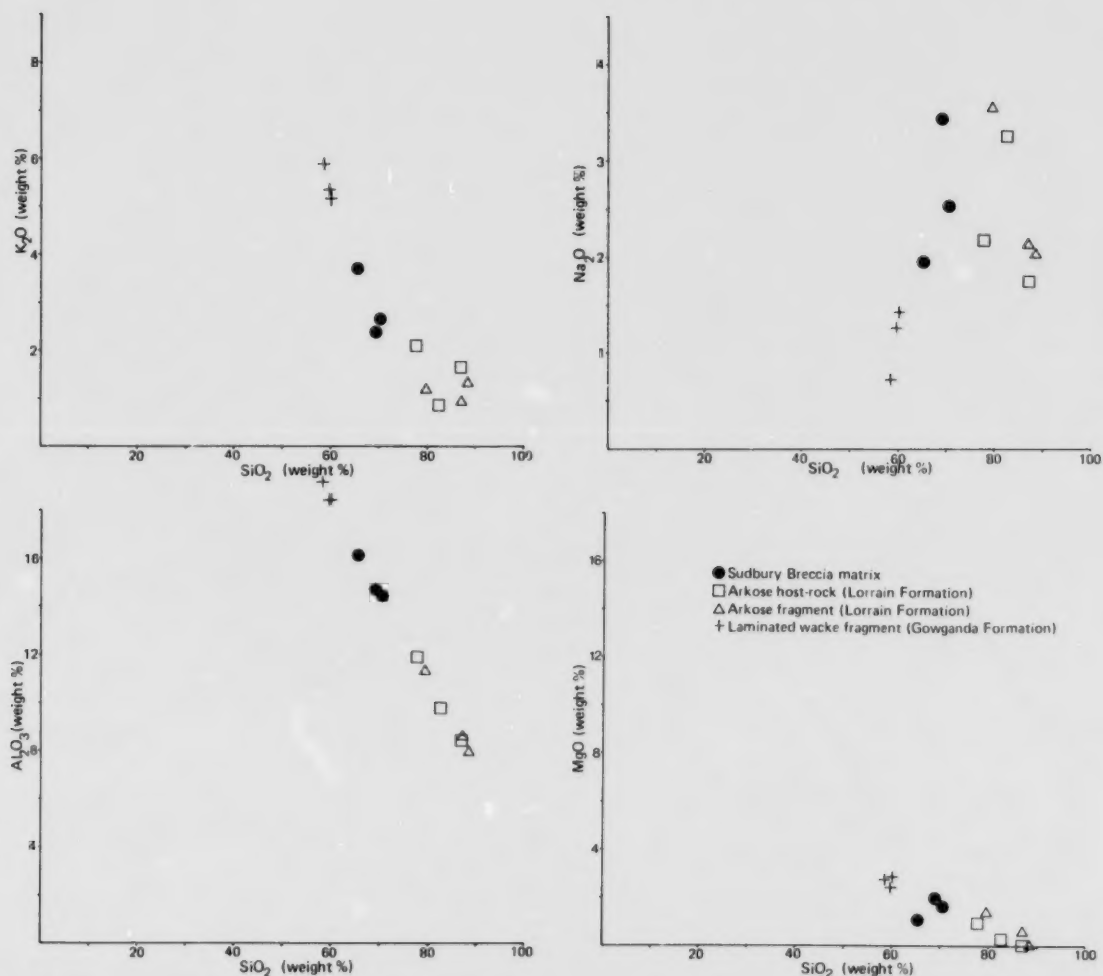


Figure 6.13. Plots of SiO₂ vs. K₂O, Na₂O, Al₂O₃, and MgO; Sudbury Breccia; central western shore of Bassin Lake, Rathbun Township.

dotachylite veinlets in thin sections of crystalline rocks ejected from the Ries crater. Dike breccias were also recorded in core obtained from a scientific drillhole put down to a depth of 1207 m, near the centre of the crater (D. Stöffler *et al.* 1977). These breccias cross-cut the crystalline basement rocks and contain first generation breccia fragments and also contain fragments of glass (Stöffler, Professor, University of Münster, personal communication, 1984). Stettner (1974) interpreted the Mesozoic rocks and the glass to have been "sucked in during the expansion of the rocks after shock compression". Graup (1977) and Hüttner (1977) concluded that the Ries dike breccias formed along pre-Ries impact faults and joints.

In the Manicouagan impact structure, pseudotachylites occur in dikes and rootless pods within the basement rocks (Dressler 1970; Murtaugh 1976).

Dikes here appear to be more common than irregularly shaped bodies or anastomosing veinlets. The fragments in the pseudotachylite are derived from the host rocks and are subangular to rounded. These fragments are embedded in a pinkish grey, red, or black matrix that commonly exhibits flow textures. The Manicouagan pseudotachylites macroscopically resemble Sudbury Breccias.

Examination of thin sections of the Manicouagan pseudotachylites reveals the presence of rock and mineral fragments that are unaltered, shock metamorphosed, or that have even been melted and presently consist of recrystallized glass. The matrix in some places consists of devitrified glass and in other places is cryptocrystalline, composed for example, of devitrified glass or very fine grained recrystallized rock flour.

ORIGIN OF THE SUDBURY BRECCIA

The origin of the Sudbury Breccia is related to the formation of the Sudbury Structure as deduced from the spatial relationship of the breccia occurrences around the Sudbury Structure.

Speers (1957) proposed a magmatic-tectonic origin for the Sudbury Breccias, and stated:

"Forces accompanying the Killarnean mountain-building were instrumental in forming a great dome structure in the Huronian and older rocks, which in turn was instrumental in guiding magma toward its apex. The central core of crystalline rocks was thrust upward as if by a punch from below, possibly by forces which resulted from magmatic action in the deeper parts of the structure, and Sudbury breccias were formed in the resulting tension fractures.

This may have been followed by the intrusion of Nipissing gabbros into the early-formed breccias. After the Nipissing gabbros had solidified, the central core of older rocks was again driven bodily upward, and gaping tension fractures developed on the old surface, especially along the old contacts. Volcanic gases burst through the centre of the dome along major rifts and thus ushered in one of the most violent periods of explosive volcanic activity ever recorded in the rocks of the earth's crust. The actual eruption was continuous and may have taken place in a relatively short period of time. Tilting and undulation of the surface, resulting from the eruption, caused multitudes of tension fractures to open and close like jaws on giant crushers. Fragments which sloughed from the walls of the gaping fissures or which tumbled into the fractures from the rubble-covered surface were crushed and ground to fine sizes. In the deeper fissures, rock-bursting played a prominent role in the development of the breccia."

French (1968) advocated a meteorite impact origin for the Sudbury Structure. Speers (1957) stated that the origin of the Sudbury Breccia, "could without serious modification, apply to the explosive after-effects of a large meteorite impact. The debate over the origin of the Sudbury structure thus concentrates less on the nature of events, and more on the source of the energy required to produce them".

Dupuis *et al.* (1982), based on chemical investigations, interpreted the Sudbury Breccia to be related to diatreme activities. These authors suggested that the breccia studied by them represented fragmented rock above an underlying fenite breccia and alkali igneous body.

The author has shown in this paper that the major chemical results of Dupuis *et al.* (1982), for example the K-enrichment, can be interpreted by a simple cataclastic mixing process involving the various rock types found in the breccia body studied.

Fairbairn and Robson (1942) excluded a direct igneous origin for the breccia. These authors concluded that "the matrices are too rich in quartz to have been molten during their formation unless unusual temperatures are assumed". They also stated that the age of the breccia is fixed as a definite finite event in the geological time scale, and that the close chemical and mineralogical relation between matrix and host rock or fragment makes a magmatic origin quite untenable. The hypothesis was also forwarded that the breccia formed by a combination of movement and hydrothermal activity which occurred after the intrusion of the gabbro, norite, and later granites.

The observations made by the author of this chapter and many other Sudbury geologists disagree with the hypothesis of Fairbairn and Robson (1942) and suggest that the breccias, in general, formed prior to the emplacement of the Sudbury Igneous Complex.

These observations also suggest that the breccias originated mainly by brittle fracture and comminution of Footwall rocks in an explosive event followed instantaneously by forceful intrusions and later readjustments of the crust. Most breccia bodies show either minor or no indications of shear movement or displacements of host rock features (*see* Figure 6.9). Such indications of movement during brecciation, however, could suggest that a directional force was involved. This force was responsible for the brecciation of the Footwall rocks, mainly along pre-existing weaknesses such as joints, faults, bedding planes, or lithological contacts. Intrusion occurred during sudden dilation after the passage of the shock waves through the rocks, when crushed rock material was forced into larger openings and fine cracks. In places, such movement possibly occurred over large distances as is indicated by the presence of "exotic" fragments in some breccia bodies. The structureless filling of some cracks commonly occurred perpendicular to breccia dikes in which a shearing component is indicated by deformed fragments and cataclastic flow. Frictional heat close to the explosive event led to partial or complete melting of crushed rock material.

Crustal readjustment following the catastrophic Sudbury Event led to more brecciation and milling of rocks in existing breccia bodies and along faults, and also to a brecciation of breccia bodies formed a little earlier. This readjustment must have occurred over a long period of time, as breccias, similar to Sudbury Breccia, have been observed in rocks of the Sudbury

Igneous Complex, for example at the Fraser Mine in Levack Township (Dressler 1981a).

The distribution of the breccia bodies around the Sudbury Igneous Complex suggests a central breccia-forming event took place. The outer, second zone of stronger brecciation suggested in Figure 6.6, however, is not explained solely by a central explosion. The author interprets the breccia-poor annulus as an analog to the acoustic "zone of silence" around large man-made surface explosions. The explosion can be heard in 2 zones, 1 close to the explosion, and in another located far away and separated by a considerable distance from the central zone (Figure 6.14). A second zone of strong brecciation at approximately a distance of 80 km from the Sudbury Igneous Complex shown by Peredery and Morrison (Chapter 22, this volume, Figure 22.4) can be interpreted in a similar manner by assuming refraction of the shock wave at deeper levels in the earth's crust or upper mantle.

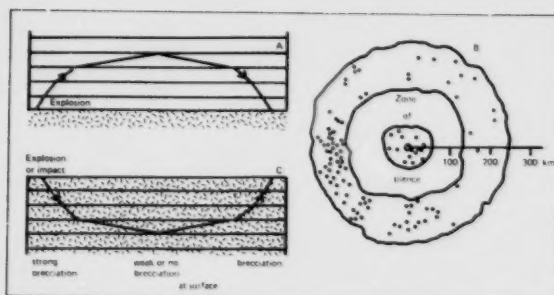


Figure 6.14. An attempt to explain the outer zone of again stronger brecciation analogous to the "Zone of Silence" around large explosions. A and B from Bergmann and Schaefer (1961) A: Path of sound wave in atmosphere. C: Path of shock wave in Footwall.

The author is aware that an acoustic phenomenon is not necessarily a good analogy for a possibly hypersonic brecciation process around the Sudbury Igneous Complex. This was pointed out to the author by one of the reviewers of this chapter, who interpreted the observations as an analogy to multiple ring systems around large impact craters where brecciation should be particularly intense.

The Froid Offset Dike, exposed outside the open pits, consists of metamorphosed Sudbury Breccia. Sublayer material is absent from the presently accessible exposures. Burrows and Rickaby (1935, p.27), however, described "quartz-diorite and another rock of gabbroic nature" in the Froid Offset Dike, and showed these rock types on their geological map (Sudbury Nickel Area, No.43d, eastern half) that accompanies their report. These gabbroic, quartz-dioritic rocks are presently mined out, but the author believes

that these rocks introduced the sulphide minerals into the pre-existing Sudbury Breccia body.

Footwall Breccia

The Footwall Breccia, also known as granite breccia or leucocratic breccia, is one of the most puzzling rock types in the Sudbury area. It contains much of the sulphide mineralization of the Sudbury Structure. As "leucocratic breccia", this rock formerly had been included in the Sublayer (Pattison 1979). It has been described under various names by several researchers (for example, Langford 1960; Pattison 1979; Muir 1981, 1983; Souch, Podolsky *et al.* 1969). No consensus has been reached as to its origin or its age-relationship with respect to the Sublayer and the Main Mass of the Sudbury Igneous Complex.

DISTRIBUTION

The Footwall Breccia forms discontinuous lenses and sheets along the lower contact of the Sudbury Igneous Complex. It is most common in the East and North Ranges. The best exposures are located in Levack Township, in an area extending from the Fecunis Lake Fault eastward to just east of the Coleman Mine (Photo 6.17); in Capreol Township, at Capre Lake; and in Trill Township, at the Trillabelle and Sultana properties. In the South Range, the Footwall Breccia was observed by the author near the Chicago Mine. Pattison (1979, Figure 11) classified the ore-bearing breccia at the Stobie Mine as "leucocratic breccia", that is, Footwall Breccia. Several small, 1 to 10 m wide, inclusion-bearing granitic bodies occur along the lower contact of the Sudbury Igneous Complex in the South Range, and may very well represent remobilized Footwall Breccia.

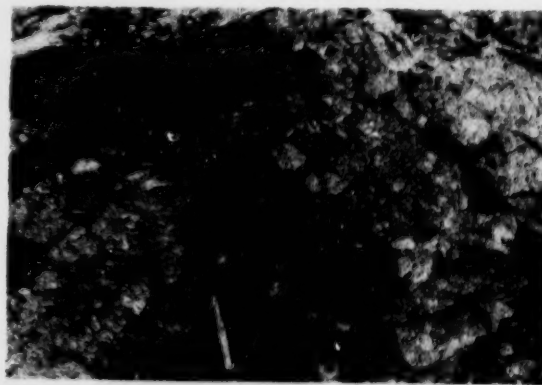


Photo 6.17. Footwall Breccia, near Coleman and Strathcona Mines, Levack Township.

The contacts of the Footwall Breccia with the norite or Sublayer of the Sudbury Igneous Complex are commonly sharp or rather abrupt. Gradational contacts with the Sublayer were observed where the Sublayer incorporated many Footwall and Footwall Breccia fragments. The presence of rusty stains and strong weathering, however, does not make an interpretation of the contact relationships possible in all places. A sharp intrusive contact of a norite apophysis into the Footwall Breccia is exposed near the eastern boundary of Levack Township, indicating a pre-norite (Lower Zone of the Main Mass) age for the Footwall Breccia (Dressler 1981a). The contact of the lower Footwall Breccia with the underlying rocks is gradational for distances of as much as over 150 m (Figure 6.15). This gradational zone, termed "megabreccia" by Pattison (1979), is characterized by autochthonous Footwall fragments, up to several 10s of m in size embedded, in and intruded by the Footwall Breccia. The Footwall Breccia forms small dikes or offshoots up to 250 m away from the main Footwall Breccia body. Small bodies of remobilized breccia also intrude the norite of the Sudbury Igneous Complex (A.J. Naldrett, Professor, University of Toronto, personal communication, 1983).

Footwall Breccia material is also found in offset dikes, as in the Foy and Whistle Offsets. It is not known if the Footwall Breccia of the offsets was transported passively as inclusions to its present positions, or if it was intruded as dikes prior to the emplacement of the Sublayer.

DESCRIPTION

Macroscopic Features

The Footwall Breccia is a heterolithic breccia characterized by a variety of angular to subrounded fragments of diverse sizes, set in a pinkish grey, grey, or dark grey matrix. The author has observed very rare sulphide fragments, up to about 5 cm in size, and fragments of medium-grained gabbro, diabase, porphyritic and glomeroporphyritic diabase, granulite facies and amphibolite-facies granodioritic and mafic gneisses, granitic rocks, mafic metavolcanic rocks, anorthosite, banded cherty ironstone, and minor Huronian arenites. Most fragments appear to be of local derivation. Anorthosite and ironstone fragments in the Footwall Breccia of Capre Lake in the East Range, however, have no local equivalents. The nearest exposed anorthosite lies 9 km to the southeast in Falconbridge Township; the nearest exposed ironstone lies approximately 10 km to the north in Rathbun Township.

Greenman (1970) studied the Footwall Breccia in and close to the Strathcona Mine in Levack Township. He described 2 phases, the "grey breccia" and the "barren breccia". The "barren breccia" contains only traces of sulphide minerals, whereas much of the nickel-copper ore at the Strathcona Mine is contained in the "grey breccia" which also has olivine-bearing inclusions similar to those of the Sublayer (Greenman 1970). Greenman did not observe the 2 breccia types in contact with each other, and therefore, could not establish their age relationship. According to him, the textures of their matrices are similar. Greenman (1970, p. 130, 131) stated that the Footwall Breccia is younger than the Sudbury Igneous Complex and the "grey breccia" is younger than the Sublayer (xenolithic norite). He advanced the hypothesis that the "grey breccia" incorporated sulphide ore, and mafic and ultramafic fragments formed the lower parts of the Sublayer during its emplacement. The author, however, has clear evidence (*see below*) from several places around the Sudbury Igneous Complex which indicates that the Footwall Breccia formed prior to the intrusion of the Sudbury Igneous Complex. The author reinterprets Greenman's (1970) "grey breccia" to be a rock formed by the incorporation of much barren breccia material in the sulphide-rich and mafic inclusion-rich Sublayer.

The inclusions in the Footwall Breccia are randomly oriented, and indicate that no large-scale movement occurred within the breccia relative to the underlying Footwall after its formation and original emplacement. Footwall Breccia dikes and veinlets, intrude the underlying host rocks and larger fragments of megabreccia, and commonly are rich in granophyre. Some of these dikes and veins consist largely of an inclusion-bearing granophyre grading into an inclusion-free granophyre away from the main breccia body (Figure 6.16). Medium- and coarse-grained to pegmatitic granophyre dikes that cut across the Footwall Breccia also exist, for instance at Capre Lake (Table 6.6). These rocks represent a mobilize formed within the breccia. In the South Range Footwall, where a deeper section of the Sudbury Structure is exposed, the remobilization possibly affected all the Footwall Breccia resulting in a granitic rock (Table 6.6) that retained only the most resistant mafic fragments.

Microscopic Features

Pattison (1979) described the matrix of the Footwall Breccia as "mosaic-granoblastic metamorphic". This characterization, however, does not encompass all the microscopic features observable in this rock.

Microscopic observations substantiate the macroscopic, heterolithic character of the Footwall Breccia (Photo 6.18). All fragment types observed

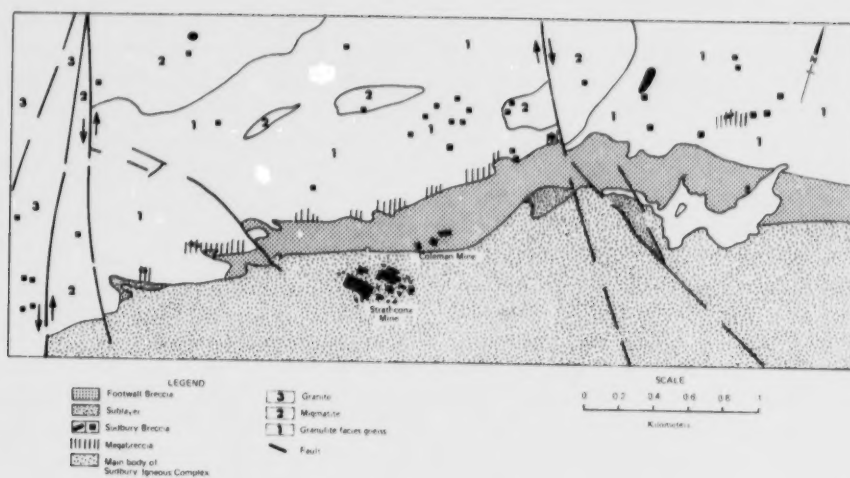


Figure 6.15. Footwall Breccia and Megabreccia in Levack Township.

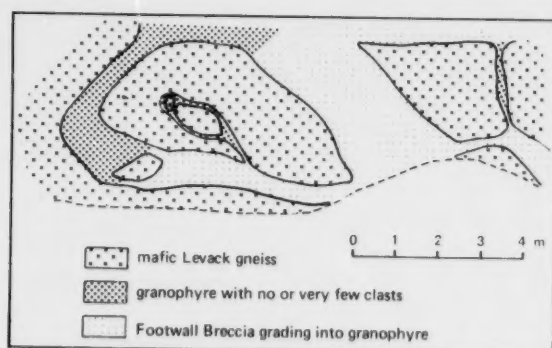


Figure 6.16. Footwall Breccia grading into granophyric mobilize.

macroscopically can also be seen in thin section as small to microscopic fragments. The rock fragments and mineral fragments are angular to rounded, and in many cases, do not have sharp boundaries with the enclosing matrix. Scarce, angular, shard-like fragments are also present. These fragments are very fine grained, recrystallized, and possibly were glass shards.

The most characteristic microscopic feature of the Footwall Breccia matrix, and also of many of the rock fragments, is the presence of small stubby plagioclase laths (Photos 6.19 and 6.20). These laths form decussate textures, or form small clusters or single crystals in porphyroblastic minerals. These laths may be clear and unaltered, or are dusty and saussuritized. Granoblastic textures of polygonal plagioclase and quartz, and a granophyric intergrowth of quartz and feldspar, also occur in the breccia matrix. The granophyric quartz-feldspar intergrowth may be indicative of partial melting. Triple junctions of polygonal plagioclase grains indicate subsolidus equilibrium. Stubby plagioclase also replaces quartz (Photo 6.20).

TABLE 6.6: WHOLE ROCK ANALYSES, FOOTWALL BRECCIA

	1	2	3	4	5
SiO ₂	64.77	56.2	72.60	73.70	71.90
Al ₂ O ₃	14.74	15.0	13.20	13.30	13.70
Fe ₂ O ₃			0.57	0.62	0.48
FeO	tot 3.64	tot 6.50	1.83	1.93	1.66
MgO	1.34	4.91	0.69	0.29	1.18
CaO	3.77	5.87	1.41	1.26	1.14
Na ₂ O	5.28	n.d.	2.57	2.60	4.07
K ₂ O	1.40	1.64	4.50	5.01	3.68
TiO ₂	0.46	0.8	0.76	0.34	0.59
P ₂ O ₅	n.d.	n.d.	0.09	0.00	0.08
MnO	0.04	0.12	0.03	0.08	0.03
CO ₂	n.d.	n.d.	0.16	0.10	0.10
S	0.21	n.d.	0.01	0.01	0.10
H ₂ O ⁺	tot 1.93	n.d.	0.62	0.47	0.97
H ₂ O ⁻	—	n.d.	0.09	0.04	0.23
NiO	0.05	n.d.	n.d.	n.d.	n.d.
CuO	0.05	n.d.	n.d.	n.d.	n.d.
Cr ₂ O ₃	0.04	0.07	n.d.	n.d.	n.d.

Notes:

1. Average "barren leucocratic breccia matrix", Strathcona Mine, n = 8, Greenman (1970)
2. Average "barren leucocratic breccia", Foy Offset n = 11, Pattison (1979)
3. Remobilized Footwall Breccia, containing some visible inclusions. Location as 4
4. "Remobilized Footwall Breccia?", inclusion free granitic rock, South Range 0.6 km east of Lockerby Mine
5. Granophyric mobilize (Dike), Capre Lake, Capreol Township

Several minerals may form porphyroblasts in the matrix. Quartz and plagioclase are the most common (Photo 6.20). Biotite, hornblende, clinopyroxene, magnetite, and potassic feldspar porphyroblasts also occur (Photo 6.21). All porphyroblasts contain inclusions of other rock-forming minerals. Quartz porphy-

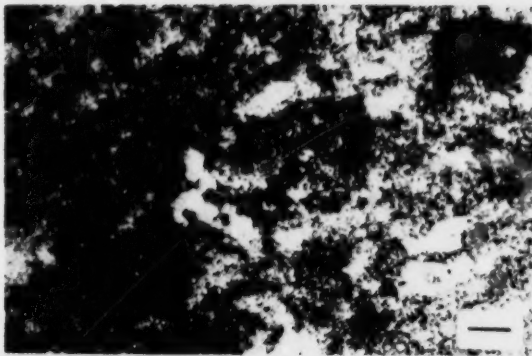


Photo 6.18. Matrix of Footwall Breccia. 0.5 km northeast of Coleman Mine, Levack Township. Plane polarized light. Scale 1 mm.

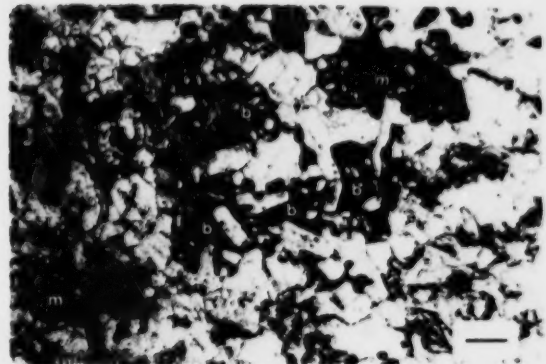


Photo 6.21. Porphyroblastic biotite (b) and porphyroblastic magnetite (m). Footwall Breccia. Trillabelle Property. Scale 0.1 mm.

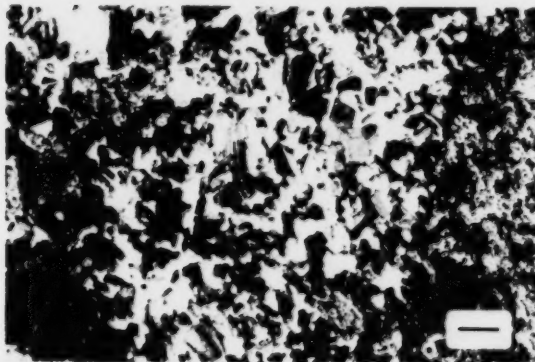


Photo 6.19. Porphyroblastic quartz (light) filled with many stubby plagioclase crystals. Footwall Breccia, Sultana Property, Trill Township. Crossed polarizers. Scale 0.25 mm.



Photo 6.20. Stubby plagioclase laths (pl) replacing quartz (Q). Leucosome of a migmatite fragment. Footwall Breccia, Bowell Township. Crossed polarizers. Scale 0.2 mm.

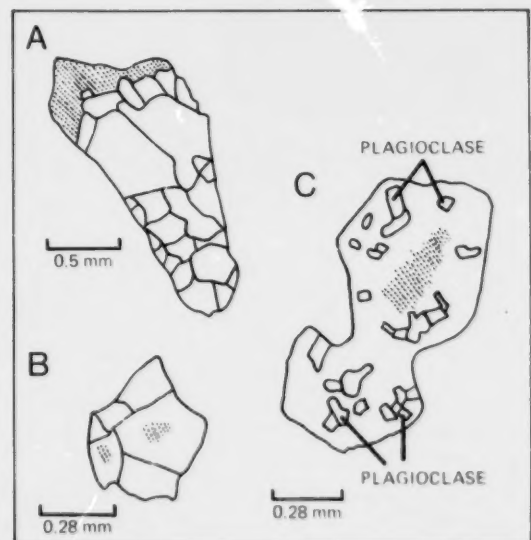


Figure 6.17. Relicts of planar features in partly recrystallized quartz. The relicts occur mainly in non-recrystallized centres of quartz grains. In grain B, parallel sets are in the centres of neighbouring quartz grains of different optical orientation.

that, in places, exhibit relict planar features (Figure 6.17). Plagioclase porphyroblasts are up to approximately 0.8 mm in size. These are untwinned, or are weakly twinned, and optically have the same composition as the plagioclase laths which they commonly enclose.

Quartz not only has grown porphyroblastically within the Footwall Breccia matrix, but also has replaced plagioclase and other minerals within both the matrix and fragments. In places, granophyre has grown around larger plagioclase laths (Figure 6.18). The central parts of granophyric intergrowths are somewhat coarser than their rims, indicating that the granophyre grew "in place" and does not represent rock fragments. In the places where granophyre lo-

roblasts are up to 1.5 mm across, in places make up to 30% of the breccia matrix, and commonly contain densely packed stubby plagioclase laths. These porphyroblasts may have grown around quartz fragments

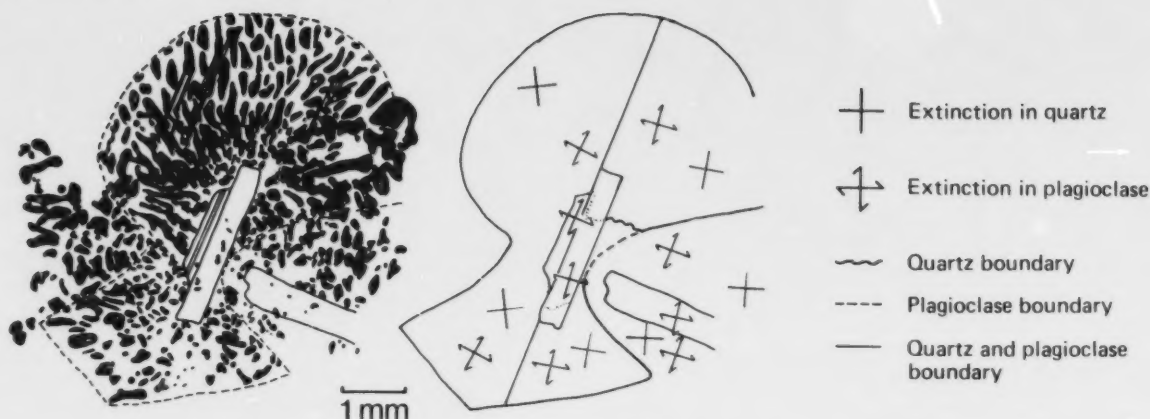


Figure 6.18. Granophyric intergrowth of quartz (black) and plagioclase. In 2 places, the Ab-rich plagioclase is twinned, the twinning being parallel to the large plagioclase crystal. The optical orientation of plagioclase in the granophyre is controlled by the 2 idiomorphic plagioclase laths.

cally forms a major component of the breccia matrix, the breccia resembles a granitic, granophyric rock, both microscopically and macroscopically.

In a few thin sections, hypidiomorphic apatite crystals were observed. These occur in the matrix and in the fragments, and are up to 0.7 by 2.4 mm in size.

Shock-metamorphic features are not common in rock or mineral fragments. Planar features in the centres of some quartz and quartzite fragments (see Figure 6.17) and kink bands in non-recrystallized micas, are the only shock features that escaped complete recrystallization. Shock-metamorphic features may have been more common in the Footwall Breccia before the intrusion of the Sudbury Igneous Complex, because they are more common away from the Complex, and are more common outside the contact-metamorphic aureole than within the aureole where the Footwall Breccia occurs. Shock metamorphism should be strongest at and near the explosion centre. One would, therefore, expect any shock features to be more common in the Footwall Breccia and "megabreccia" than they are. Instructive in this regard is the presence of recrystallized plagioclase in Footwall Breccia fragments of gabbro containing non-recrystallized, relatively unaltered pyroxene and hornblende (Photos 6.22 and 6.23).

The author believes that plagioclase recrystallization is not after saussurite or unaltered plagioclase, but is after strongly shocked plagioclase, possibly after maskelynite, because, during retrograde regional metamorphism, pyroxene and hornblende normally break down to form actinolite or chlorite before plagioclase shows much alteration (Dressler 1982). In contradistinction to shock metamorphism, mafic minerals are more resistant to alteration than feldspars, and may occur as modestly deformed or unaltered individ-

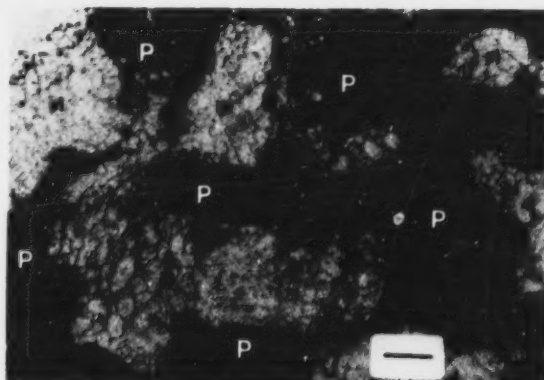


Photo 6.22. Subophitic gabbro. Relicts of pyroxene (P); plagioclase (Pl). North Range Footwall. Plane polarized light. Scale 0.2 mm.

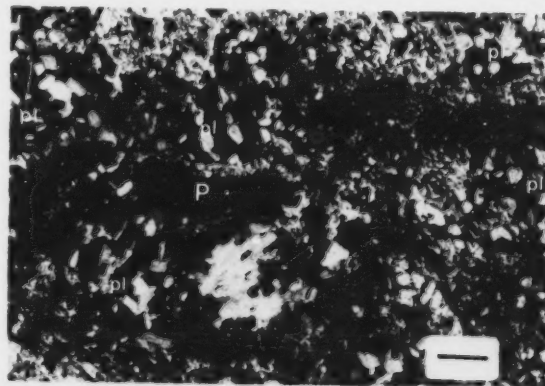


Photo 6.23. Subophitic gabbro. Relicts of clinopyroxene (P). North Range Footwall. Crossed polarizers. Scale 0.2 mm. (same thin section as Photo 6.22).

uals embedded in maskelynite (Dressler 1970). The author, therefore, believes that the presence of recrystallized plagioclase in gabbroic rocks containing rather unaltered pyroxene and hornblende suggests that the recrystallization occurred from diaplectic plagioclase, possibly from maskelynite. Shock-metamorphic features, therefore, were more common in the Footwall Breccia before the contact-metamorphic overprinting due to the intrusion of the Sudbury Igneous Complex.

The temperatures at which the annealing of shock-metamorphic features took place can be estimated by studying the contact metamorphic mineral assemblages, including those of the Footwall Breccia, near the Sudbury Igneous Complex. Observations on recrystallized shock-metamorphic rocks similar to the ones described above, were made by Schreyer (1983). Ostertag (1981) performed annealing experiments on diaplectic feldspar glasses and noted that diaplectic oligoclase glass recrystallized at temperatures above 900°C. Ostertag's experiments substantiate the results obtained by Bunch *et al.* (1967) and by Dressler (1970). These authors also substantiate the author's interpretations of the microscopic observations made on samples of the Footwall Breccia.

CHEMICAL INVESTIGATIONS

No attempt has been made by the author to chemically study the Footwall Breccia. A few chemical analyses listed in Table 6.6 reflect the heterolithic character of the Footwall Breccia.

ORIGIN OF THE FOOTWALL BRECCIA

The Footwall Breccia occurs mainly adjacent to the Sudbury Igneous Complex of the North and East Ranges, where a level of the Sudbury Structure is exposed that is possibly 3 to 5 km higher in the crust than that exposed in the South Range (Naldrett *et al.* 1970). The North and East Range Footwall Breccia bodies are much thicker than those of the South Range. These features and the distribution of the Footwall Breccia, suggest that the latter was formed along the upper parts of a Sudbury crater wall.

The Footwall Breccia components have been affected by several geological processes. The brecciation and shock metamorphism probably are related to a single event. The contact-metamorphic overprint was caused by the intrusion of the Sudbury Igneous Complex. A later period of regional metamorphism followed and obliterated many primary features. At the deeper South Range level, the temperature increase due to the intrusion of the norite magma of the Sudbury Igneous Complex was high enough to melt the small breccia bodies and possibly parts of the Footwall rocks to form granitic mobilizates. The original nature

of the breccia matrix is no longer clearly recognizable because of contact metamorphic overprint, partial remobilization, and/or melting. The petrographic features of the North Range breccia bodies can be more easily interpreted than those of the South Range. The author believes that the Footwall Breccias originally consisted of a predominantly parautochthonous mass of crushed, and pulverized, partly shock-metamorphosed rocks. The Footwall Breccia appears to grade into Sudbury Breccia bodies, the weakly metamorphosed matrix of which consists in most places of finely crushed rock powder.

Sulphide fragments in the Footwall Breccia possibly represent brecciated pre-Sudbury event sulphide bodies, as do the sulphide fragments in the Onaping Formation. The large sulphide ore bodies within the Footwall Breccia in several of the mines of the Sudbury district were introduced into the breccia tectonically and/or as sulphide magmas.

The Footwall Breccia, to the author's knowledge, has no equivalent in volcanic regimes. In contradistinction, terrestrial breccias, similar to those described here, occur in the Ries impact crater in Germany (Geologica Bavarica 1974). Peredery (1972b) compared the various breccias of the Ries crater with the breccias of the Sudbury Structure. Dressler (1983) found microscopic and macroscopic similarities between the Footwall Breccia and lunar fragmental, polymict breccias.

RELATIONSHIPS OF THE FOOTWALL BRECCIA WITH OTHER ROCK UNITS OF THE SUDBURY STRUCTURE

An understanding of the relationship of the Sudbury Breccia and the Footwall Breccia is important to the interpretation of the origin of the Sudbury Structure. If the structure originated in a single, catastrophic event such as a meteorite impact, the 2 breccias should be contemporaneous or almost contemporaneous.

In the Levack Township Footwall Breccia, a mafic gneiss fragment was found to be cut by a Sudbury Breccia dikelet. This suggests that the Sudbury Breccia is older. On the other hand, just northeast of the Coleman Mine, also in Levack Township, and on the Sultana property in Trill Township, the Footwall megabreccia appears to grade into Sudbury Breccia over distances of 10 to 20 m (Photo 6.24). In outcrops closer to the main Footwall Breccia bodies and the Sudbury Igneous Complex, typical Footwall "megabreccia" is exposed, whereas farther away, typical Sudbury Breccia occurs. In the transition zone between, Sudbury Breccia dikes merge with brecciated host rocks, that in turn appear to merge with typical "megabreccia". The matrix of the transitional breccia has similar charac-

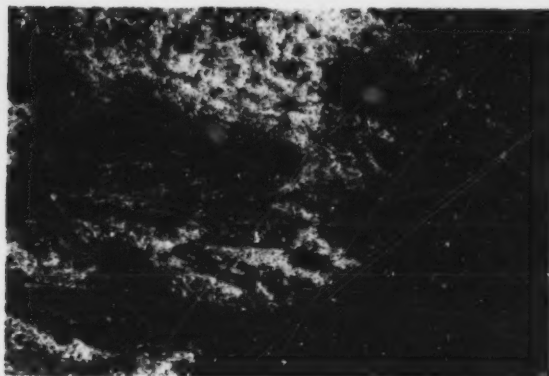


Photo 6.24. Transition Sudbury Breccia–Footwall Breccia. 0.5 km northeast of Coleman Mine, Levack Township. (Camera lens cap is 5 cm in diameter).

teristics to those of both the Footwall Breccia and the Sudbury Breccia matrices.

The observations are contradictory. Nevertheless, the occurrence of the fragment of Sudbury Breccia in the Footwall Breccia, namely, the occurrence of multiple breccias in 1 deposit, is not conclusive evidence that the 2 breccias were not formed by contemporaneous processes. Multiple breccias have been formed in the Bunte Breccia (Hörz *et al.* 1983) and in the suevite (G. Graup, Max Planck Institut für Chemie, Mainz, personal communication, 1983) of the Ries impact crater in Germany. The author does not wish to imply that Sudbury Breccia and Footwall Breccia were produced by the same process. The above observations suggest that originally, both breccias simply consisted of crushed rocks and that as pointed out previously, the Footwall Breccia has features indicative of contact metamorphism related to the intrusion of the Sudbury Igneous Complex. The Sudbury Breccia, however, has features merely reflecting a pervasive regional metamorphism.

The Footwall Breccia and Sudbury Breccia are probably related to the first stages of the development of the Sudbury Structure. These breccias originated before the emplacement of most other rock units related to the Sudbury Structure.

An apophysis of norite originating from the Sudbury Igneous Complex intrudes the Footwall Breccia just east of the Coleman Mine (Dressler 1981a) in Levack Township. Plagioclase laths occurring within the norite that occurs very close to the Footwall Breccia and around inclusions of Footwall Breccia, are, in plates aligned parallel to the norite–Footwall Breccia contact (Muir 1983). These observations indicate that the norite is younger than the Footwall Breccia. In the past (Pattison 1979, p. 265), noritic gabbro fragments in the breccia at the Strathcona Mine were interpreted

to be derived from the Sudbury Igneous Complex norite, suggesting that the Footwall Breccia is younger than the norite. The fragments could have been derived from a Nipissing gabbro intrusion, a pre-Sudbury event rock unit.

The Sublayer locally projects into and contains inclusions of the Sudbury Igneous Complex norite (Naldrett *et al.*, Chapter 11, this volume). In places, it also has elongate inclusions and plagioclase laths aligned parallel to the Sublayer–norite contact. The Sublayer is post-norite in age, and therefore, is younger than the Footwall Breccia. Further evidence for this conclusion is indicated by the occurrence of Footwall Breccia inclusions within the Sublayer at several places in Trill Township.

The relationship of the Footwall Breccia to the Basal Member of the Onaping Formation is uncertain. Some similarities exist between the 2 rock units, but some major differences also are present. Locally, the Basal Member resembles the Footwall Breccia, for example in a rock cut along the road that leads from Highway 545 to Ella Lake in Capreol Township (T.L. Muir, Geologist, Ontario Geological Survey, personal communication, 1980). Examination of thin sections made from rocks taken from this road-cut reveals the presence of stubby plagioclase recrystallization typical for rocks underlying the North and East Range Sudbury Igneous Complex. In most other places, however, the Basal Member (Muir and Peredery, Chapter 7, this volume) is different from the Footwall Breccia. For instance, the Basal Member contains only very few mafic rock fragments and many more and much larger fragments of Huronian arenites than does the Footwall Breccia. The matrix is also different (Muir and Peredery, Chapter 7, this volume). Further, it is hard to imagine that the Sudbury Igneous Complex would have intruded exactly along a contact of 2 physically similar breccia units, that is, along the contact between the breccias of the Basal Member of the Onaping Formation with the Footwall Breccia. Evidence exists that the Complex cuts across lithological units. Such evidence is the variable thickness and, in places, the absence of the Footwall Breccia. The author speculates that the Footwall Breccia and the Basal Member of the Onaping Formation originally belonged to 1 breccia sequence, with a lower parautochthonous (Footwall Breccia) unit and an upper allochthonous (Basal Member) unit.

CONTACT METAMORPHISM OF THE FOOTWALL ROCKS

The Footwall rocks including the Sudbury Breccia and the Footwall Breccia, were subjected to contact meta-

morphism in a zone that is up to 1.2 km wide adjacent to the Sudbury Igneous Complex. This zone is characterized by the occurrence of stubby to decussate, recrystallized plagioclase. Similar plagioclase also occurs in fragments in the Onaping Formation above the Sudbury Igneous Complex (W.V. Peredery, Staff Geologist, Inco Limited, personal communication, 1983). In the South Range Footwall rocks, contact-metamorphic mineralogy and textures have been all but obliterated due to a strong post-Sudbury Igneous Complex regional metamorphic overprint that also affected the South Range Sudbury Igneous Complex itself.

In Levack Township (Figure 6.19), in the North Range, the contact metamorphic aureole was investigated by the author. Within the aureole, the following assemblages of recrystallized minerals can be recognized:

1. clinopyroxene-plagioclase
2. clinopyroxene-(brown-green) hornblende-biotite-quartz plagioclase
3. Clinopyroxene-biotite-quartz-plagioclase
4. Biotite-hornblende-quartz-plagioclase
5. Biotite-quartz-plagioclase
6. Quartz-plagioclase

Based on these contact metamorphic mineral assemblages, facies boundaries are drawn in Figure 6.19.

The contact-metamorphic recrystallization did not alter the primary rock textures. In an ophitic gabbro, for instance (see Photos 6.22 and 6.23), decussate plagioclase fills the spaces between the primary, magmatic plagioclase laths and in banded gneisses it replaces the primary, granoblastic plagioclase. In hand

specimen, the contact-metamorphic recrystallized rocks still exhibit their primary textures and the recrystallized plagioclase can be recognized by a porcelainous lustre.

The anorthite content of the stubby, decussate plagioclase does not show any trend within the contact metamorphic zone. The optically determined anorthite content reflects the primary plagioclase composition, and there is no Ca-increase as one approaches the Sudbury Igneous Complex. Within the zone of contact metamorphic plagioclase recrystallization, the size of the plagioclase stubs increases from 0.06 mm farthest away from the Complex to 0.33 mm very close to it. Contact metamorphic plagioclase does not only occur in stubby, decussate form, but, in the Footwall Breccia matrix, also occurs as porphyroblasts or as granophyric intergrowths with quartz (Photo 6.25). Porphyroblasts of quartz and other minerals also occur in the rocks.

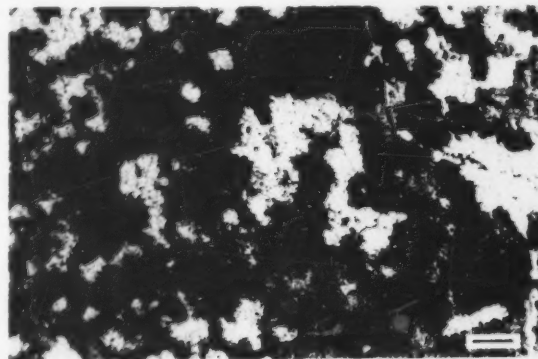


Photo 6.25. Incipient melting, granitic fragment in Footwall Breccia (recrystallized), 0.5 km northeast of Coleman Mine, Levack Township. Plane polarised light. Scale 1.5 mm.

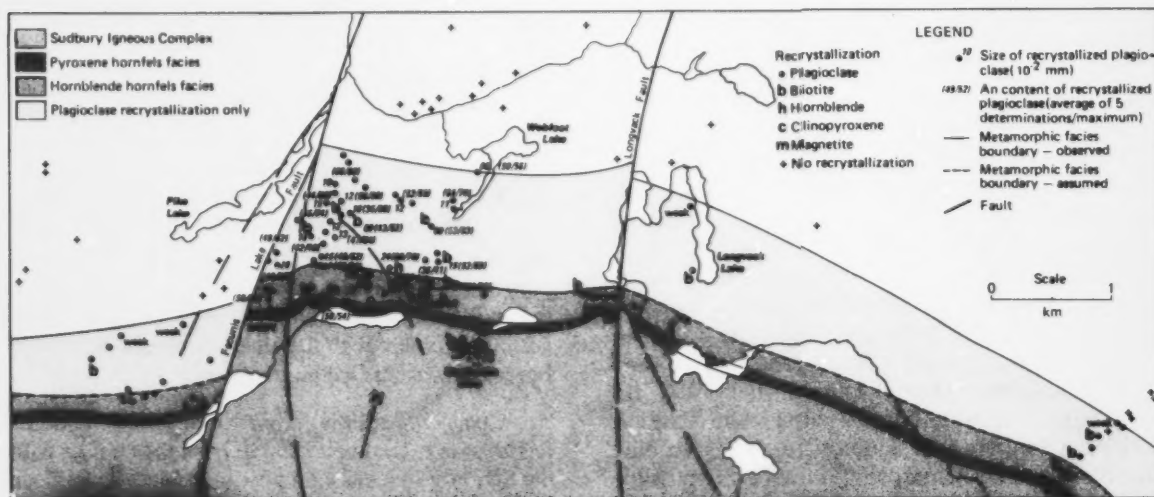


Figure 6.19. Contact Metamorphism, Levack Township.

Contact-metamorphic recrystallized, clear, and unstrained quartz forms polygonal aggregates replacing larger primary quartz crystals. Individual grains within these aggregates may be idiomorphic. Some larger, not completely recrystallized grains may contain relicts of planar features in dusty centres surrounded by clear quartz. Relicts of decorated planar features, that is, the aligned decorations alone, without the connecting lamellae, can also be seen cutting across grain boundaries of recrystallized quartz. Or the relicts have the same orientation in neighbouring quartz crystals (Figure 6.17). Schreyer (1983) made the same observations on recrystallized quartz in basement rocks of the Vredefort Dome and stated that "the fluid inclusions (the decorations) have fully retained their positions in the quartz volume despite the growth of new quartz crystals".

Contact-metamorphic biotite, hornblende, and clinopyroxene are clear, show no kink bands or deformation bands in spite of their close proximity to the Sudbury Igneous Complex. Commonly, these minerals contain inclusions of contact-metamorphic plagioclase stubs. Hypidiomorphic to xenomorphic magnetite containing stubby plagioclase occurs in a few places.

Incipient melting is indicated by textures in some granitic fragments in the Footwall Breccia, and in a few places is indicated in granitic Footwall rocks very close to the Sudbury Igneous Complex. The incipient melting is of a contact-metamorphic and/or shock-metamorphic origin.

An accurate estimate of the physical conditions under which the Footwall rocks were contact metamorphosed cannot be made. The depth at which the Sudbury Igneous Complex was intruded into the crust and the Proterozoic geothermal gradient are not known. It is also unknown what temperature increase resulted from the Sudbury Event. If the Sudbury Basin has a volcanic origin, a volcanic area existed with an especially high geothermal gradient. Similarly, a higher than normal temperature in the Footwall has to be assumed if a meteorite impact was the crater-forming event. The residual, or after-shock temperature can be roughly estimated. The Footwall rocks located approximately 1.2 km distant from the Sudbury Igneous Complex belong in Chao's (1968a, 1968b) zone 1 of shock-metamorphic alterations. This zone is characterized by planar features in quartz and feldspars and by a residual temperature of approximately 80°C. An accurate estimate of the residual temperature in the immediate vicinity of the Sudbury Igneous Complex based on shock-metamorphic features is not possible because such features were almost completely de-

stroyed by later contact-metamorphic recrystallization. A conservative estimate of the residual temperature before intrusion of the Sudbury Igneous Complex is 100° to 200°C.

The pre-erosion depth of the intrusion of the Sudbury Igneous Complex is not known. Naldrett *et al.* (1970) stated that the South Range of the Sudbury Igneous Complex has been elevated approximately 5 km with respect to the North Range along faults that dip steeply and that parallel the long axis of the Sudbury Basin. Dence (1972, p. 15) assumed removal of 5 km of rock by "normal" erosion to obtain the present level of basin exposure.

The pre-Sudbury Igneous Complex temperature of the basement at an assumed depth of 5 km cannot be estimated with a high degree of confidence. A conservative figure for both the volcanic and impact scenario is 200° to 250°C.

Naldrett and Kullerud (1967) assumed that the Sudbury Igneous Complex was a rapidly intruding hot (1000°C) norite sheet, which had a 20°C per 1 km geothermal gradient, and was emplaced at a depth of 5 km. These authors concluded "that the country rocks adjacent to the Nickel Irruptive (Igneous Complex) at one time have been at a high temperature, around 700°C, for over 300,000 years, that for some of this period the temperature gradient was very steep (60°C per 100 feet, 180°C per 100 m); and that for all of this period the temperature gradient was moderately steep (at least 14°C per 100 feet, 42°C per 100 m)". According to Naldrett and Kullerud (1967, Figure 22A), the Footwall rocks approximately 220 m away from the Sudbury Igneous Complex were at about 600°C (pyroxene hornfels facies) 720 000 years after the intrusion.

The albite-epidote hornfels facies starts at a temperature of somewhat under 400°C, the hornblende hornfels facies at approximately 520° to 540 ± 20°C, and the pyroxene hornfels facies at 580° to 630 + 20°C (Winkler 1967).

In Figure 6.19, the hornfels facies zones are narrower than one would expect according to these estimates. W.V. Peredery (Staff Geologist, Inco Limited, personal communication, 1983) has evidence of clinopyroxene in Sudbury Breccia up to 500 m away from the Sudbury Igneous Complex, an observation that is not in agreement with the author's observation from Levack Township (see Figure 6.6).

Coats *et al.* (1984) reported the pyroxene hornfels zone to extend up to 250 m from the contact with the Sudbury Igneous Complex, a distance very close to that determined by Naldrett and Kullerud (1967).

CONCLUSION

Until the early 1960s, the geological community in general had accepted a volcanic or tectonic-volcanic origin for the Sudbury Structure. It was in 1962, at the beginning of the modern era of impact-cratering studies, that Robert S. Dietz proposed a meteorite impact origin for the Sudbury Structure. This unconventional proposal generated new interest in Sudbury geology, and since then many scientific papers, both in favour of or against an impact origin, have been published (see Giblin, Chapter 1, this volume).

It is not the purpose of this somewhat descriptive chapter to discuss the origin of the Sudbury Structure in depth (see Muir, Chapter 21, this volume; Peredery and Morrison, Chapter 22, this volume). The author's investigations of the Footwall rocks, however, resulted in some new observations and expanded the data on many of the older observations. Because of the size of the Sudbury Structure and its complex geology, these investigations are far from complete. A conclusive theory on the origin of the Sudbury Structure cannot yet be made with a high degree of confidence at the time of writing.

The author favours a meteorite impact origin for the Sudbury Structure, even though he has only studied the Footwall of the Sudbury Structure and has less than complete knowledge of the rest of the Structure.

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WHITEWATER GROUP

CHAPTER 7

The Onaping Formation

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Editorial Note

The Sudbury Volume committee recommended that this paper should be written by these 2 people, both of whom have studied the Onaping Formation intensively over the past several years. Since these authors have reached different conclusions as to its origin, this inevitably imposed considerable difficulties upon them. The committee recommended that the authors should write a purely descriptive paper, thus eliminat-

ing all interpretation. The authors have done as requested, even though this has introduced problems as to the terminology they could use, and has resulted in descriptions that have less focus than otherwise would have been the case. The editors wish to point out that these shortcomings are the responsibility of themselves and the committee, not the authors. The editors believe that these descriptions, however, will be of great use to those unfamiliar with the Onaping Formation. Two discussions follow the paper in which

each author has been given a restricted amount of space in which to discuss his views of the interpretation. The authors were told that their discussions would receive a minimum of peer editorial review.

ABSTRACT

The Onaping Formation of Middle Proterozoic age, is the lowermost formation of the Whitewater Group in the Sudbury Basin. Along its base, the Onaping Formation is intruded by granophyres of the Sudbury Igneous Complex, and near its top, the formation grades into the overlying Onwatin Formation slates. On the South Range, the Onaping Formation is deformed.

The formation is subdivided into 4 major units, 3 of which are members. The lowermost, Basal Member, is discontinuous and comprises a variety of monolithic and heterolithic breccias consisting of material probably derived from the Superior Province basement and the overlying Huronian Supergroup. Overlying the Basal Member is the Gray Member, which consists of breccias and breccia units comprising various mixtures of country rocks and devitrified and recrystallized glasses. The Gray Member is overlain by the Black Member, which, in general, is similar to the Gray Member but, in addition, has chloritized shard-like fragments and carbonaceous material in the matrix.

Local, mesoscale stratification of limited lateral extent in both the Gray and Black Members is indicated by sharp or abruptly gradational contacts. Although each member generally dips at moderate angles toward the central part of the Sudbury Basin, some of the individual units dip away from the centre. Other units strike at angles distinctly different from those of the upper and lower contacts of the formation.

Melt Bodies comprise the fourth subdivision. These tend to occur in clusters near the Basal Member/Gray Member contact, but also occur within all 3 members. The Melt Bodies are igneous-textured, consist of crystalline central parts and chilled margins, and contain country rock inclusions which are similar to fragments in the Basal Member.

Spherulitic and flow-banded dikes intrude the Gray and Black Members. Gabbroic dikes and olivine diabase dikes intrude the Onaping Formation.

Many of the metasedimentary, granitic, gneissic, and gabbroic country rock fragments in the Onaping Formation, particularly on the undeformed North and East Ranges, display shock-metamorphic features such as planar features in quartz and feldspar. These minerals also commonly have fine mosaic and devitrification textures. Various types of glass fragments include: fluidal-textured glasses, which are chemically heterogeneous; and "simple" and "complex" glasses, based on present textures and mineralogy. Composite fragments occur throughout the Gray and Black Members and comprise breccia within

breccia, glass within glass, and complicated combinations of glass, breccia, and fluidal-textured material. Other fragments include microbreccia, sulphides (some may be replacement minerals), accretionary and armoured fragments, and single crystals of quartz, feldspar, and other minerals.

Whole rock chemical data show that the matrix of the Onaping Formation is more mafic at the top than at the bottom. Microprobe data on the fluidal glasses and whole rock data on the Melt Bodies show considerable variation in some elements.

GENERAL DESCRIPTION

The Onaping Formation (Figure 7.1; Map 2491, back pocket) is the lowermost formation of the Whitewater Group and lies entirely within the Sudbury Basin. The formation is 53 km long, 17 km wide, and has an estimated thickness of up to 1600 m. Volume estimates of the Onaping Formation range from 530 km³ (Coleman 1905), to 1250 km³ (Williams 1957), to 1670 km³ (Stevenson 1972). Granophyres of the Sudbury Igneous Complex intrude the base of the formation. The contact with the overlying Onwatin Formation is gradational.

The Onaping Formation has been interpreted to consist of ash-flow tuffs and lavas (Thomson 1957; Williams 1957; Stevenson 1972) or impact fallback breccias and impact melt (French 1967; Dence 1972; Peredery 1972b).

The Onaping Formation is stratified and divided into 4 major units. Three of these members are the lowermost Basal Member, which is overlain by the Gray Member and then by the upper Black Member. Thicknesses given for members of the Onaping Formation are approximate, and assume, for the units in the North Range, a dip of 30° (based on information from diamond-drill logs submitted for assessment work; Muir 1983).

Each member consists of a variety of breccias in numerous units, many of which are too small to map at a scale of 1:50 000. The breccias consist of any combination of fragments of country rocks, glassy material¹, fluidal material², minor sulphide mineralization, and finely comminuted matrix material. A significant proportion of the country rock fragments display shock-metamorphic features. Many of the breccias contain more than one type of glass fragment.

¹There is no glass remaining in the Onaping Formation. All 'glass' is either devitrified or recrystallized and presently ranges from microcrystalline to fine grained. The terms "glass" or "glassy", used throughout this chapter, refer to the assumed primary state of the material; such references involve some interpretation.

²Fluidal-textured material is very fine grained, dense, and has what is interpreted to be flow banding. The material may have been in a hot plastic or molten state before solidifying.

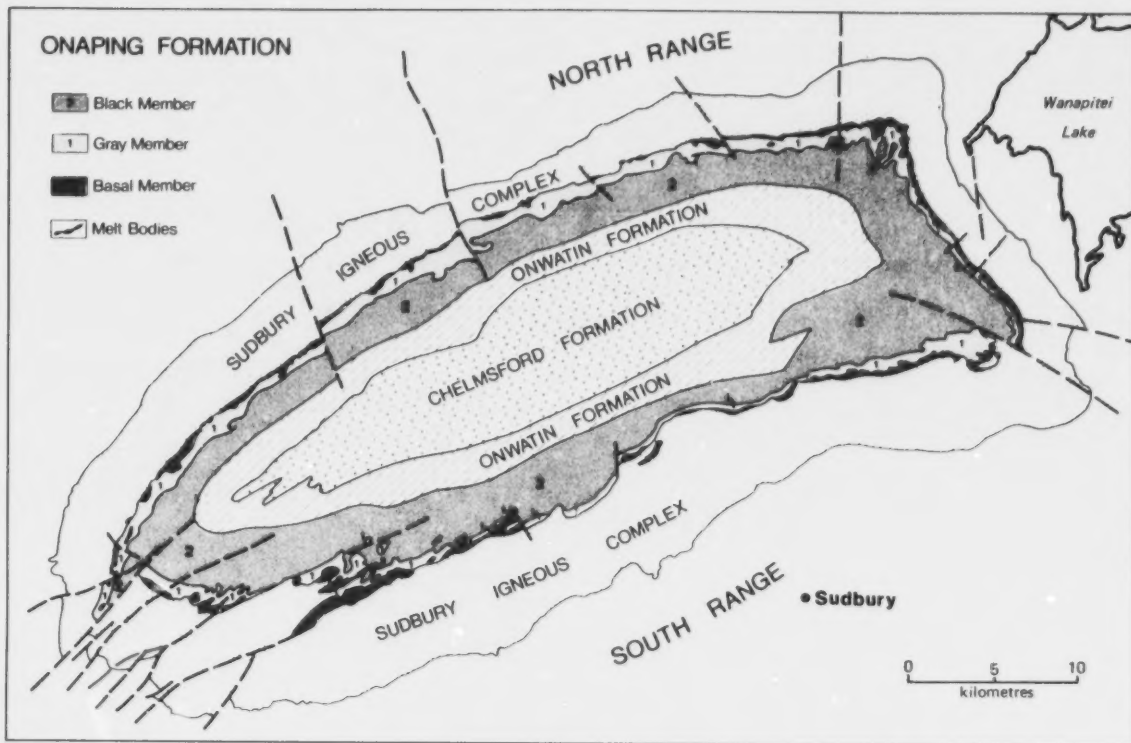


Figure 7.1. General geology of the Onaping Formation showing major subdivisions: Basal Member, Melt Bodies, Gray Member, and Black Member.

Igneous-textured inclusion-bearing Melt Bodies comprise the fourth major subdivision of the formation and occur mainly between the Basal and Gray Members, but also within all members.

The North Range is essentially undeformed, whereas the South Range has locally undergone weak to strong deformation (*see* area between Gordon and Emma Lakes, Map 2491, back pocket). Stevenson (1961) briefly described deformation in the Basal Member. Rousell (1975, 1976, and 1980) discussed foliations, lineations, kink bands, and crystallographic orientation in quartz crystals.

Nomenclature

Previous subdivisions of the Onaping Formation are shown in Table 7.1. Some terms for these subdivisions express a genetic connotation. We propose a system that is reasonably non-genetic and which allows for future subdivisions within the context of accepted stratigraphic nomenclature. Table 7.1 compares present and past terms and excludes examples which do not refer to specific mappable units. The present term "Melt Body" is expressly used to refer to the inferred molten state of such bodies, and not to a specific genetic process for that state, such as lava or impact melt.

In order to refer specifically to breccias that have different characteristics, the authors have used a simplified system based on the proportion of different fragment sizes that is modelled after Fisher (1966). The system is expressly used here as a convenient field classification with no inference to the origin of the Onaping Formation. The system divides breccias into 5 major types numbered 1 to 5 (Figure 7.2). The breccias are composed of 3 sizes of fragments: those < 2 mm diameter; those from 2 to 64 mm diameter; and those > 64 mm diameter. To maintain a simple classification, rocks consisting largely of angular to sub-rounded particles < 2 mm diameter are also considered to be "breccias". Locally, there are mappable varieties of breccia within each major type of breccia, based on lithological properties such as contacts and predominant shape, type, or size of fragments. What is referred to as matrix is relative to the scale of observation. Figure 7.3 illustrates the relationship between the matrix and the type of breccia for various scales.

Figure 7.4 represents a generalized composite stratigraphic column through the Onaping Formation, showing the major features of each subdivision. Figures 7.5 and 7.6 show 2 areas mapped in detail (within Dowling, Blezard, and Garson Townships) by Peredery (1972a). Figure 7.7 shows an area mapped in de-

CHAPTER 7

TABLE 7.1: NOMENCLATURE—PRESENT AND PAST.

PRESENT STUDY		PAST STUDIES					
MUIR AND PEREDERY	MUIR (1983, 1981)	PEREDERY (1972a, 1972b)	STEVENSON (1961, 1972)	THOMSON (1957) WILLIAMS (1957)	BURROWS AND RICKABY (1930) ^a	COLEMAN (1905)	BELL (1893)
Black Member	Black Member	black Onaping	black tuff	andesitic tuff, tuff-breccia	volcanic tuff, tuff, flow breccia	pyroclastic sediments	siliceous volcanic breccia
Gray Member	Green Member	gray Onaping	grey tuff	lapilli-tuff, glowing avalanche deposits			
Melt Body	Grey Member	melt rock, melt body	pepper-and-salt micro-pegmatite (chilled)	andesite with rhyolite fragments	lavas	part of Trout Lake Conglomerate (with igneous-looking matrix)	(unspecified)
Basal Member	Basal Member	basal breccia	quartzite breccia (tectonic)	rhyolite, rhyolite breccia	rhyolite, agglomerate	Trout Lake Conglomerate	quartzite conglomerate

Notes:

^aSome of the pre-1960 volcanic terms are based on definitions which are different from those currently in use.

^bSimilar terms were used by Moore (1930) and Cooke (1946).

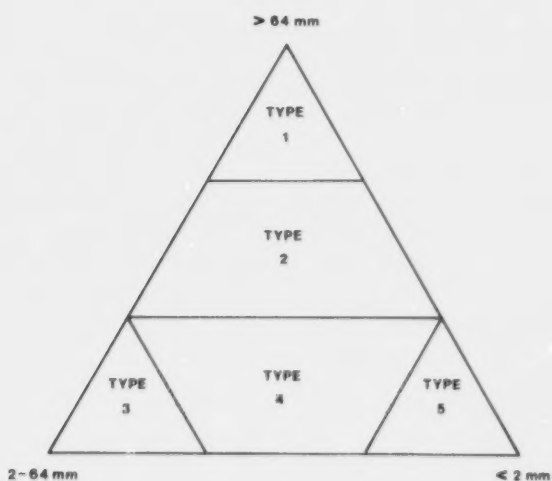


Figure 7.2. Classification of the breccias of the Onaping Formation into 5 Types based on proportions of 3 ranges in size of the constituent fragments. Modified after Fisher (1966).

tail (within Capreol Township) by Muir (1982). These figures illustrate the complexities of the Onaping Formation.

BASAL MEMBER

The Basal Member is discontinuous (Figure 7.1) and is intruded by the Upper Zone of the Sudbury Igneous Complex. Where the Basal Member is absent, the Gray Member or Melt Bodies are in contact with one or both types of granophyre which may contain inclu-

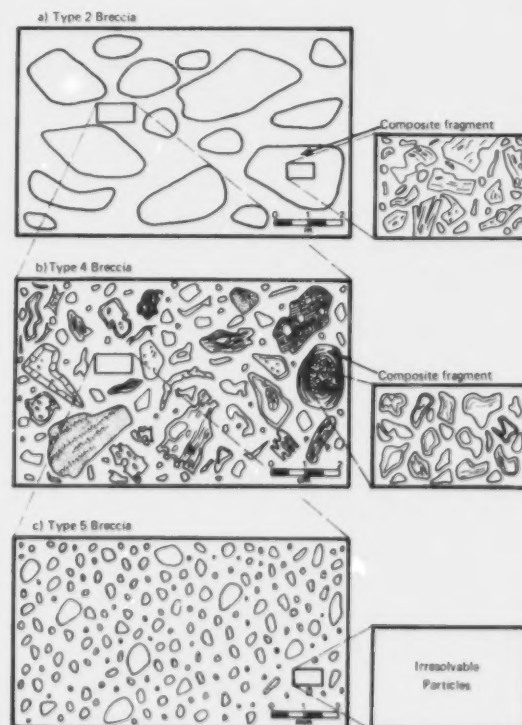


Figure 7.3. Relationship between fragments and matrix relative to the scale of observation (outcrop, hand specimen, thin section). Examples shown are composites of features found in the Onaping Formation.

sions of the Gray and Basal Members, or in uncommon cases, of the Melt Bodies.

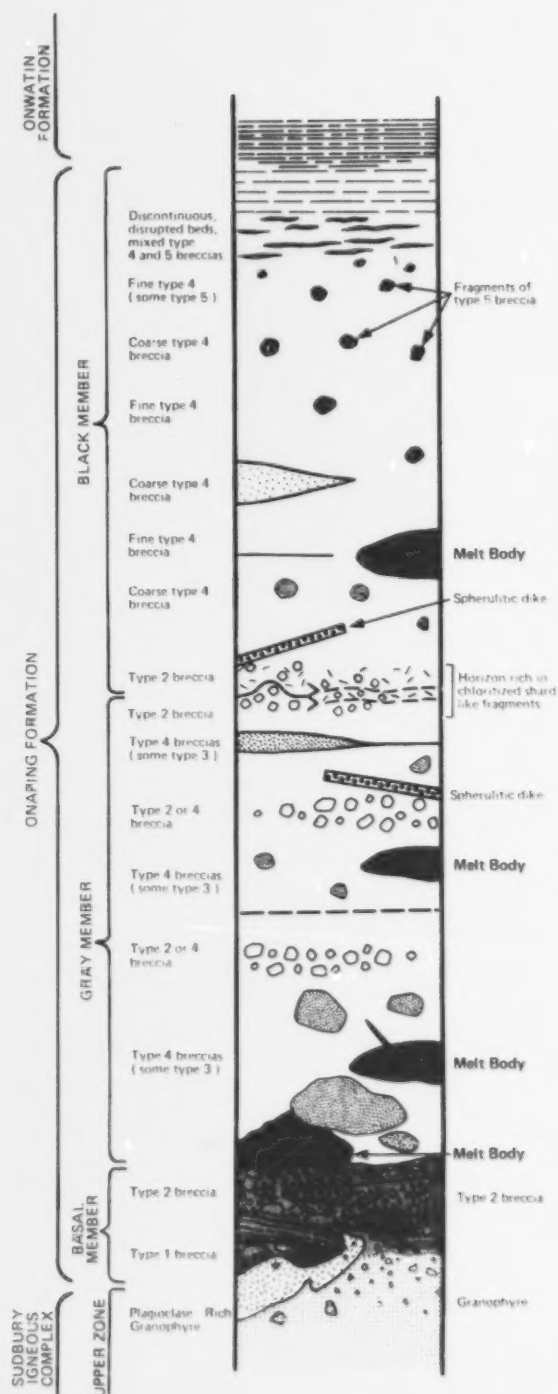


Figure 7.4. Generalized composite section through the Onaping Formation. Sketch shows a variety of relationships within and among members, Melt Bodies, and granophyres of the Sudbury Igneous Complex. Solid and stippled fragments represent country rocks; patternless fragments in Type 2 or Type 4 breccias represent various country rock, fluidal-textured, and composite fragments. Randomly oriented dashes represent the horizon rich in chloritized shard-like fragments. Longer, parallel dashes represent the gradation from the Gray Member to the Black Member. Sketch not to scale.

Large inclusions of Basal Member up to several hundred m long occur in the Upper Zone of the Sudbury Igneous Complex in Rayside, Blezard, and Lumsden Townships. Inclusions in the granophyres, in general, range from a few mm to 2 m in diameter and have either distinct, sharp outlines or diffuse boundaries up to several cm thick. The inclusions are lithologically and petrographically similar to the fragments in the Basal Member.

The contact between the plagioclase-rich granophyre of the Upper Zone of the Sudbury Igneous Complex and the Basal Member is characterized by inclusion-free, plagioclase-rich granophyre grading into inclusion-bearing, plagioclase-rich granophyre. This is in sharp contact with the Basal Member. One of the authors (W.V. Peredery) has observed similar relationships at the contact between the normal granophyre and the Basal Member. Others (Coleman 1913; Burrows and Rickaby 1930; Moore 1930; Stevenson 1963; Muir 1983) have described this particular contact as irregular and transitional. Stevenson (1963) has given the term "pepper-and-salt micropegmatite" to the matrix of the Basal Member and to some of what are now termed Melt Bodies. Muir (1983) has used the term "hybrid granophyre" to describe the inclusion-bearing contact zone of the normal granophyre. The zone contains sparse to numerous fragments of the Basal Member that range from a few mm to a few m in diameter, and from well defined to poorly defined, depending on the degree of assimilation. The fragments lie in a granophyric matrix which has a heterogeneous texture and composition (modal and chemical). No sharp intrusive contacts were found between the hybrid granophyre and the Basal Member.

There are sufficient differences in the fragments and matrices of the breccias of the Basal Member in the North and South Ranges to justify describing them separately. Descriptive details are based largely on well-exposed areas in Dowling and Garson Townships. The change from the North Range to the South Range Basal Member occurs approximately in the middle of Capreol Township, and at the Cameron Creek Fault.

Basal Member in the North Range

The Basal Member in the North Range occurs as a discontinuous layer generally < 150 m, but locally up to 300 m thick. Fragments and matrix vary considerably in lithology and in their relative proportions. Outcrops weather beige and white to light grey. Commonly, there is little contrast between small fragments and matrix.

Two main varieties of breccia, termed "matrix-supported" and "fragment-supported" (Photo 7.1) grade into one another. Fragment-supported breccias consist of tightly packed fragments, mostly > 64 mm diameter, with the matrix comprising from < 5% to an



Figure 7.5. Detailed geology of the Onaping Formation in part of Dowling Township (modified after Peredery 1972a).

arbitrary upper limit of 25%. The fragments may be so tightly packed and similar as to be delineated only by slight differences in texture from one fragment to another. The matrix-supported breccias consist of loosely packed fragments, mostly >10 mm diameter, supported by the matrix which forms up to 75% by

volume. Fragments are erratically distributed in terms of shape, size, and rock type.

Type 1 breccias of the Basal Member comprise fragment- and matrix-supported varieties. Type 2 breccias are by far the most common and are mostly

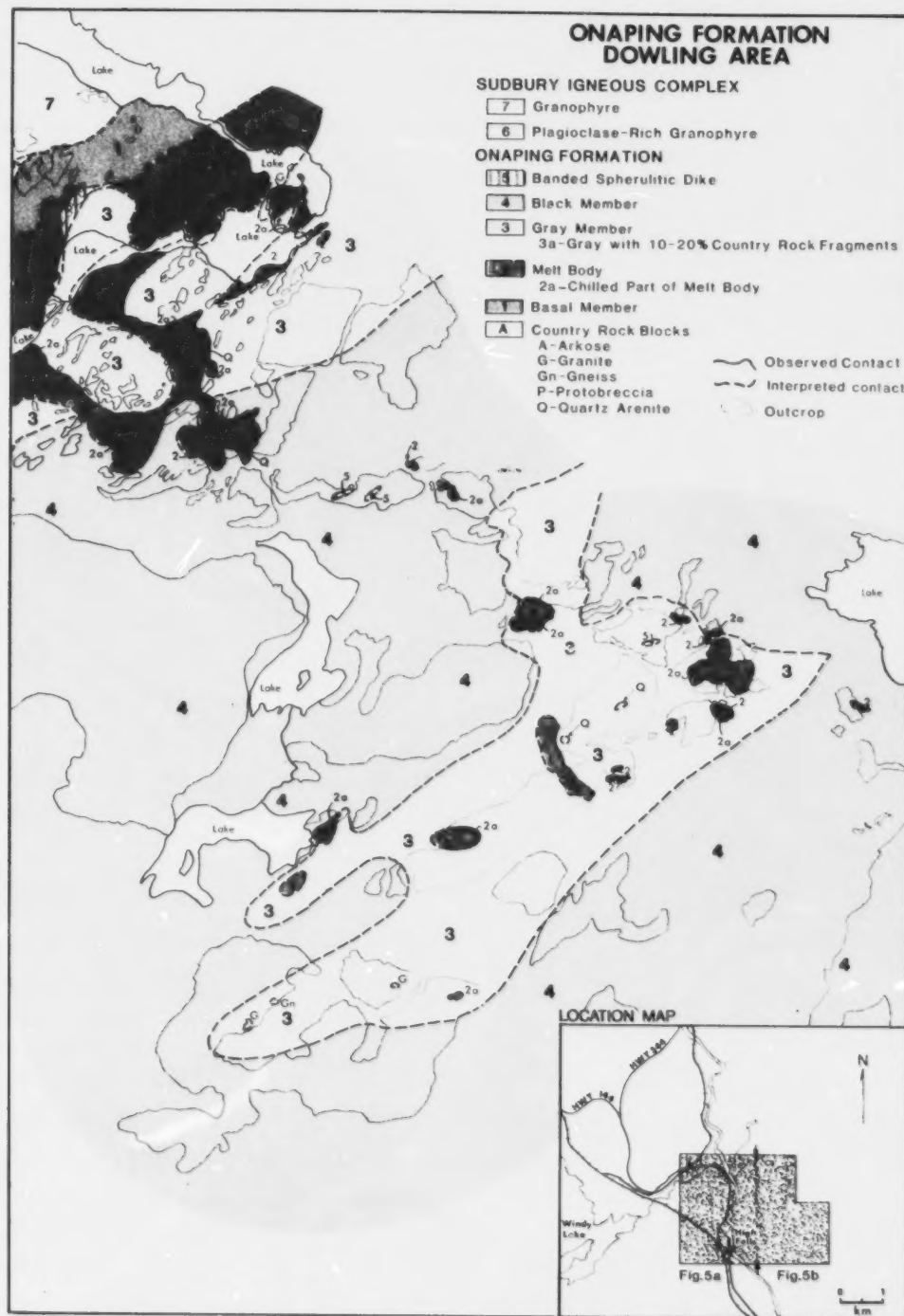


Figure 7.5. Detailed geology of the Onaping Formation in part of Dowling Township (modified after Peredery 1972a).

matrix-supported. Type 4 breccias are matrix-supported. Table 7.2 gives the proportions of the components of the Basal Member in a specific area in Dowling Township.

FRAGMENTS

The fragments comprise a variety of country rock

types. Many fragments consist of massive to foliated varieties of white to pink leucocratic granite, granodiorite, and trondhjemite. Some of the granitic fragments have pink microcline phenocrysts up to 3 cm long. Fragments of pegmatite and gneiss are also commonly present. Most Basal Member outcrops have fragments of metamorphosed, white, quartz arenite

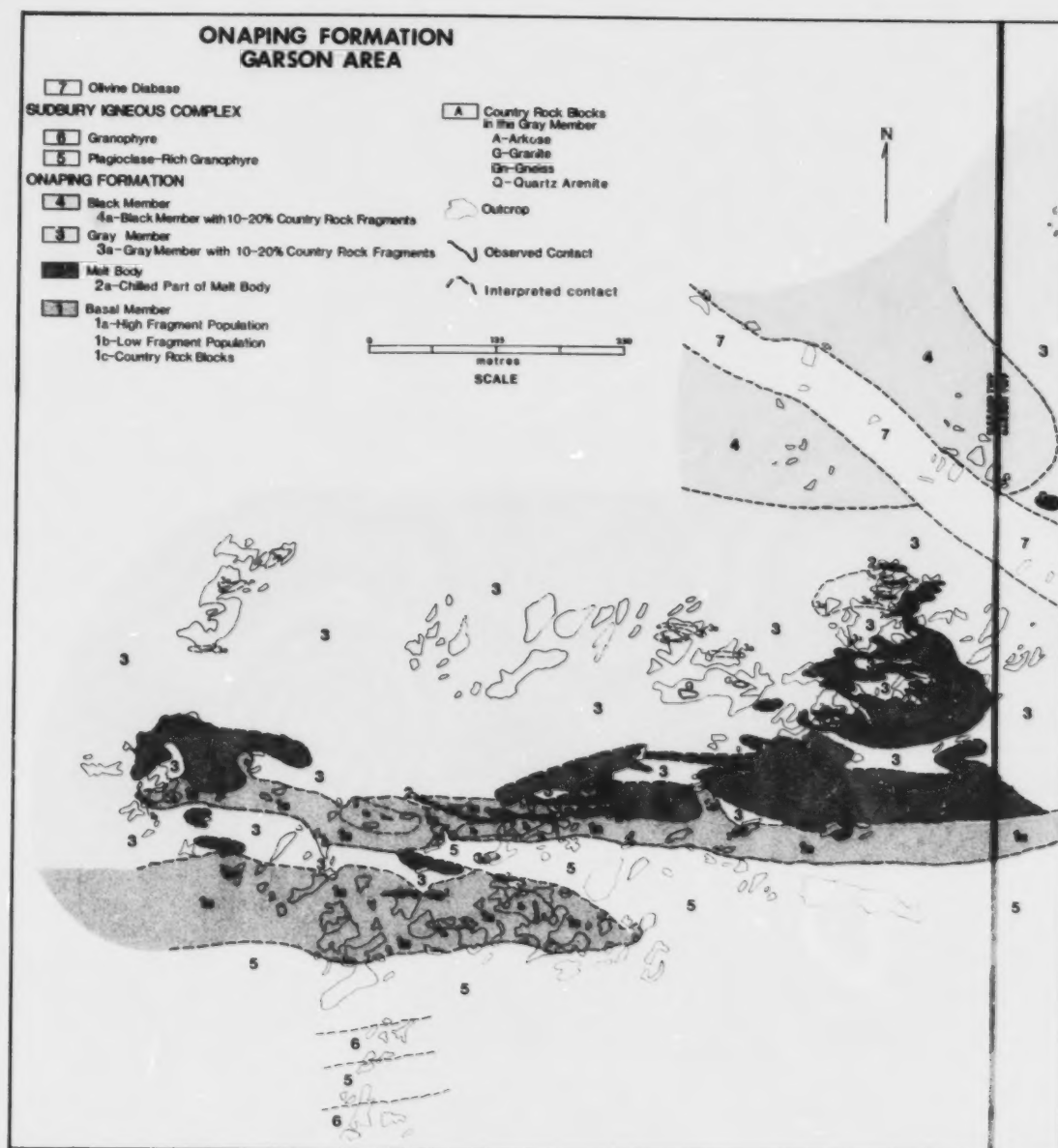


Figure 7.6. Detailed geology of the Onaping Formation in part of Garson and Blezard Townships (modified after Peredery 1972a).

and arkose. Some of these fragments were studied in detail (Onyejekwe 1982). In some locations, as in Dowling Township west of Highway 144 and in southeast Capreol Township, white metasedimentary fragments predominate. Minor metasedimentary fragments including yellow-green sericitic quartz arenite, conglomerate, quartz, and chert-like material may also be present. The sericitic arenite is commonly recrystallized and has white to beige quartzofeldspathic margins. Some of the quartz arenite is finely interlayered with chloritic laminae. The fragments of metasedimentary rocks are generally considered to be derived from the Huronian Supergroup. Fragments of mafic gneiss, gabbro, amphibolite, and diabase are

much less common and are erratically distributed. Table 7.2 compares abundances of fragments from specific localities in the North and South Ranges.

Country rock fragments in the Basal Member have various sizes and shapes. Some blocks of metasedimentary rocks are up to 100 m and more in diameter, but, generally sizes range from several cm to about 1 m. The mafic fragments are generally < 0.5 m in diameter. The shape of some fragments is controlled to a certain extent by the pre-existing structures in the rocks such as bedding or gneissosity. Fragments of gneissic and layered sedimentary rocks are rectangular or slab-like, whereas the massive arkose and



Figure 7.6. Detailed geology of the Onaping Formation in part of Garson and Blezard Townships (modified after Peredery 1972a).

granite fragments are commonly sub-angular to sub-rounded and more or less equidimensional. Some fragments have irregular shapes. Some of the quartzofeldspathic fragments have indistinct outlines, and appear to merge with the matrix because they are surrounded by numerous small fragments of similar material.

The smaller leucocratic fragments appear to have partly disintegrated in the matrix (Photos 7.2 and 7.3); some closely spaced fragments appear as if they could be fitted back together. Most fragments are white and feldspathic or quartzofeldspathic; some are pink. They have a dull appearance on fresh surfaces and a chalky appearance on weathered surfaces. The quartz is com-

monly greyish and in some fragments, particularly quartz arenite, it is nearly black. This is a peculiar feature of quartz in some country rock fragments in the Onaping Formation.

Many of the quartz-feldspar fragments have unusual textures. Quartz, commonly surrounded by feldspar, is present with feldspar in a ratio from 1:2 to 1:4, and has round, oval, and amoeba-like or embayed shapes in some fragments (Photo 7.2) and subangular to cuneiform shapes in other fragments (Muir 1981, 1983). These quartz 'domains' commonly range from 1 to 5 mm long and rarely are up 1 cm long. The feldspar commonly forms a continuous 'network' analogous to Swiss cheese with the 'holes' filled either by

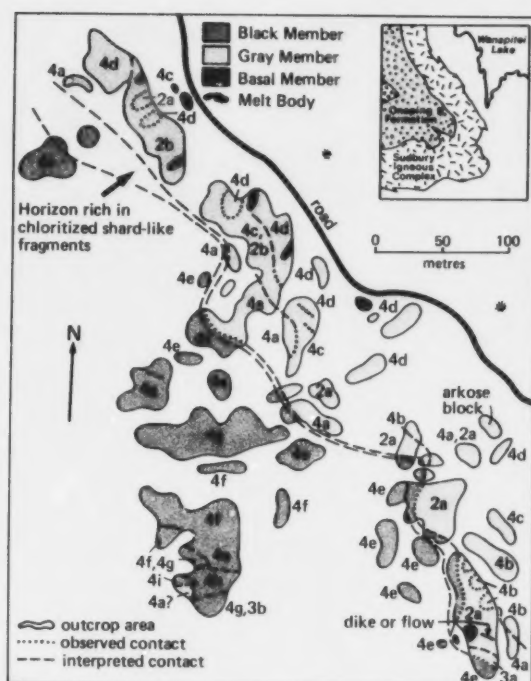


Figure 7.7. Detailed geology of the Onaping Formation in south-east Capreol Township. Numbers denote Type of breccia (see Figure 7.2). Letters denote mappable varieties of a particular Type of breccia. Contacts were observed between some of the different breccias as indicated. Modified after Muir (1982).

quartz or by the matrix of the Basal Member (Photo 7.2). Potassic feldspar commonly rims the quartz (Photo 7.3). The ratio of quartz, plagioclase, and potassic feldspar gives the fragments compositions corresponding to granite, granodiorite, and trondhjemite. Some arkosic fragments have similar mineral proportions, but display clastic textures. Some fragments consist of quartz which forms the 'network', and potassic feldspar which rims embayed and subrounded 'domains' of plagioclase.

In thin section, the quartz is commonly very fine grained to fine grained, anhedral to granular, and forms a mosaic texture of crystals which are separated in some areas by thin rims of cryptocrystalline feldspathic material. The potassic feldspar also is very fine to fine grained and occurs as anhedral laths or as poorly to moderately well developed intergrowths with quartz. Some of these quartz crystals may be rod shaped. The plagioclase is microcrystalline and displays splaying or swirling extinction patterns reminiscent of devitrified glass (Photo 7.4). Plagioclase grains also have an apparent plastically deformed shape. These textures constitute the extreme end-member of a spectrum ranging to normal igneous textures, all of which are observed in fragments throughout the Onaping Formation and in some of the Footwall rocks (Muir 1983).

TABLE 7.2: BASAL MEMBER COMPONENTS: DOWLING AND GARSON AREAS.

	Dowling Area Estimated %	Garson Area Estimated %
Rock fragments 5 cm and larger	30-40	60-70 ^a 10-25 ^b 50-60 ^c
Rock fragments 5 cm and smaller	25-35	5-10 ^a 45-30 ^b 25-20 ^c
Matrix—quartz, feldspar, mafic minerals	25-35	25-35 ^a 45-35 ^b 25-20 ^c
Rock Fragments	Estimated abundance (in %) of all the rock fragments 5 cm and larger in the Basal Member	
	Dowling Area	Garson Area
Arkose, quartz arenite, and conglomeratic quartz arenite, iron formation; chert; argillaceous metasedimentary rocks	65%	95%
Granitic and granodioritic rocks; porphyritic and pegmatitic varieties included	20%	5%
Quartzofeldspathic gneisses + mafic bands	14%	—
Mafic (amphibolitic) rocks; gabbro	1%	—

Notes:

Estimated proportions of Basal Member components in Dowling area (see Figure 7.5) and Garson area (see Figure 6); modified after Peredery (1972a)

^a variety of Basal Member breccia with relatively high proportion of country rock fragments

^b variety of Basal Member breccia with relatively low proportion of country rock fragments

^c lens of Basal Member breccia within Gray Member (see Figure 7.6)

MATRIX

The matrix weathers light grey to rusty brown, is light to medium grey on fresh surfaces and is generally quartzofeldspathic. Disseminated throughout the matrix are acicular and anhedral mafic minerals which give the rock the "pepper-and-salt" texture originally described by Stevenson (1963); (Photo 7.5).

The matrix is fine grained (locally medium grained), heterogeneous, and ranges from highly recrystallized to igneous-textured (Photos 7.3, 7.5, and 7.6). The heterogeneity is most evident on a thin-section scale as shown by:

1. a range in grain size from fine to medium grained with local patches of coarser grained crystals within finer grained crystals (Photos 7.3, 7.5, and 7.6)
2. varied proportions of the major minerals

3. numerous irregularly distributed, small, white to pink inclusions of very finely recrystallized feldspathic material, finely recrystallized quartz (Photo 7.3), and, in some cases, oval, quartzose, amygdale-like features

4. sparse clots of mafic minerals

The matrix in the lower part of the Basal Member tends to be coarser grained and tends to contain more potassic feldspar than in the upper part.

The modal mineralogy of the matrix, excluding the small clasts, ranges widely from sample to sample. The main minerals are plagioclase (35 to 60%), quartz (25 to 45%), potassic feldspar (10 to 40%), and mafic minerals such as chlorite, amphibole, and rarely clinopyroxene (5 to 15%). Mafic minerals are significantly more abundant in the matrix than in the enclosed country rock fragments. Accessory minerals are ilmenite and apatite. The ilmenite commonly occurs as needles < 0.4 mm long (Photo 7.6) and/or as anhedral grains. Secondary minerals include granular epidote-group minerals, titanite, and leucoxene. Some epidote crystals have yellowish to light brown colours and appear similar to allanite found in the Upper Zone of the Sudbury Igneous Complex. Minor pyrite and some pyrrhotite also occur in the matrix as small (< 3 mm) irregularly shaped patches.

The plagioclase is either subhedral, equant, or more commonly, lath shaped, ranges from very fine grained to medium grained, and generally has an albitic composition as determined by microprobe analyses (*see* section on Petrochemistry). Albite twinning is commonly developed in the larger grains which also contain irregularly shaped patches of antiperthite. The plagioclase shows a dusty, very fine grained alteration similar to that in the Sudbury Igneous Complex. The potassic feldspar is fine to medium grained, commonly perthitic, has a prismatic habit, and is locally intergrown with quartz in a crudely developed micrographic intergrowth (Photo 7.6).

The quartz is very fine to fine grained, either equigranular or anhedral with angular outlines, and locally occurs as optically continuous patches up to 4 mm across. In some thin sections, quartz appears to be recrystallized after elongate rod-shaped crystals, possibly pseudomorphous after tridymite (Photo 7.6). This form of quartz commonly occurs around or within inclusions. The rod-shaped habit is best seen in plane light.

Chloritization of the mafic grains has generally been extensive and in some cases has been complete. Amphibole is the second most abundant mafic mineral, has an uneven green pleochroism, and forms elongate prismatic crystals up to 4.5 mm long (generally < 1 mm) and subequant to equant crystals up to 1.0 mm across. The equant crystals, where present, are commonly partly or completely altered to chlorite, and

are generally larger than the prismatic crystals. Some chlorite appears to be pseudomorphous after subhedral crystals of amphibole. Rocks from the upper part of the Basal Member uncommonly have some clinopyroxene crystals. In these cases, Melt Bodies generally occur nearby. The clinopyroxene crystals are subhedral to anhedral, equant to elongate, lack twinning, and commonly occur in clusters. Their fine-grained nature is similar to the pyroxenes in the Melt Bodies. Results of microprobe analyses are given in the section on Petrochemistry.

Associated with some of the granitic, granodioritic, or gneissic fragments are fine- to medium-grained stringers and patches of igneous-textured material (Photo 7.5). The stringers and patches occur:

1. wholly within fragments, parallel to gneissosity
2. within but at the margins of fragments, generally truncated against the matrix of the breccia
3. partly surrounding fragments
4. within the matrix

These stringers are composed of fine- to medium-grained laths of feldspar, dark green mafic minerals such as clinopyroxene, amphibole, and chlorite, and some quartz. The stringers have a texture similar to, but finer grained than, the plagioclase-rich granophyre lenses in the Basal Member.

Basal Member in the South Range

The Basal Member in the South Range is up to several hundred m thick, has a greater variety of breccias than in the North Range, and has been tectonically deformed and metamorphosed. Locally, the breccias are only slightly deformed; however, these breccias tend to be lithologically different from the strongly deformed breccias. Lenses of Basal Member occur also in the overlying Gray Member (Figure 7.6). They are up to a few m wide and up to several 10s of m long.

The Basal Member in Garson Township is characterized by fragment-supported and locally matrix-supported breccias of Types 1 and 2 (Photos 7.7 and 7.8) consisting mostly of white to cream-coloured quartz arenite. Many fragments show no primary sedimentary features, but bedding (Photo 7.8), crossbedding, and rounded quartz pebbles were found locally. East of the Canadian National Railway, the quartz fragments display strongly deformed bedding. Thomson (1957) referred to these rocks as flow-banded rhyolite. Stevenson (1961) interpreted them to be quartzite deformed as a result of either soft-sediment deformation (prior to brecciation) or tectonic processes (post-brecciation).

Greenish-yellow, sericitic, quartz arenite fragments up to 10s of m long occur locally in the eastern part of Garson Township. The fragments commonly contain quartz pebbles or thin beds of conglomerate

with rounded quartz pebbles and granules. The matrix to these fragments is medium to dark grey and is commonly foliated or schistose. Locally, there are parts of the Basal Member that consist of well-sorted Type 3 breccias with quartz arenite fragments similar to the above breccias. These Type 3 breccias locally form units within Types 1 and 2 breccias, parallel or sub-parallel to the regional strike of the Sudbury Basin. Table 7.2 gives the proportions of the components of the Basal Member in a specific area in Garson Township.

Parts of Rayside and Blezard Townships are characterized by Type 2 Basal Member breccias, which locally are quite similar to typical Basal Member breccias of the North Range. The matrix is light to medium grey on fresh surfaces and weakly foliated to massive. The fragments consist of white quartz arenite, arkose, quartz, and leucocratic granitic fragments. In exposures, the matrix is fine grained and appears granitic. The percentage of fragments is difficult to determine. Locally, the fragments appear to have partly disintegrated in the matrix in the same manner as seen in the North Range. Large fragments are virtually absent.

Creighton Township has breccias similar to those in Garson Township. Fairbank Township has breccias with a white to cream-coloured matrix (light grey to medium grey on fresh surfaces), a predominance of white quartz arenite, and a greater than normal variety of other types of quartz arenite, arkose, quartz, minor leucocratic granitic rocks, and rare, sericite-rich rocks.

FRAGMENTS

In general, most fragments in the Basal Member are recrystallized and tectonically deformed quartz arenite consisting of up to 95% quartz and 5% very fine grained feldspathic material. The feldspathic material is chess-board albite (Stevenson 1961). The quartz grains are anhedral, weakly to strongly strained, and locally are opalescent blue on fresh surfaces. In some of the breccias, the quartz occurs as recrystallized masses of anhedral or polygonal crystals with a mosaic texture. Fragments of quartz-sericite metasedimentary rocks locally are recrystallized along their margins to quartzofeldspathic rocks texturally similar to quartz arenite.

Granitic fragments are similar to those in the North Range in that they have cryptocrystalline plagioclase and granular, mosaic-textured quartz. Uncommon, layered (bedded?), cleaved, sericitic, schistose fragments are scattered throughout parts of the Basal Member, particularly in Creighton and Fairbank Townships. These fragments consist of 35 to 90% very fine grained sericite, with fine-grained feldspar and up to 30% medium-grained crystals or groups of crystals of subhedral plagioclase.

MATRIX

The matrix ranges from white to cream on weathered surfaces and from medium grey to very dark grey on fresh surfaces. It is fine to medium grained and contains up to 40% of small pieces of the same rock types that constitute the larger fragments.

Thin section examination reveals the matrix to consist of very fine grained plagioclase, quartz, potassic feldspar, sericite, chlorite, and green to brown biotite. Fine-grained foliated mafic minerals are responsible for the generally darker matrix of these rocks compared to the lighter coloured matrix of the Basal Member of the North Range. Due to recrystallization, most crystals are anhedral and more equant than in the North Range. Any micrographic intergrowth between quartz and potassic feldspar is crudely developed. Commonly, there are some larger, anhedral, irregularly shaped crystals of feldspar and/or quartz (up to 1 mm diameter) throughout the matrix. Most crystals have interlocking, locally sutured boundaries. In other respects, the matrix is similar to that of the North Range.

MELT BODIES

The description of Melt Bodies in this section is largely derived from the North Range occurrences. Melt Bodies in the South Range are similar to these except that they have been affected by deformation and metamorphism, particularly those bodies adjacent to the Basal Member.

Most Melt Bodies occur as lens-shaped or irregularly shaped bodies which are locally concentrated in clusters at or near the base of the Gray Member. Other Melt Bodies occur in the Basal, Gray, or Black Members. The overall outline of some clusters is roughly triangular in plan with one of the sides abutting the Basal Member and the other sides protruding into the Gray Member. Peredery (1972a) reported sharp contacts between the Melt Bodies and the Basal Member in Dowling and Garson Townships. Stevenson (1963) and Muir (1981, 1983) noted some cases of a gradational contact between what are presently termed Melt Bodies, and the Basal Member in the South and North Ranges. Contacts with the Gray Member are sharp. Where the Basal Member is missing, Melt Bodies are in sharp contact with the Sudbury Igneous Complex (Peredery 1972a). In the South Range, most of the clusters of what are presently termed Melt Bodies are deformed and attenuated parallel to the foliation (Stevenson 1963). The size of these clusters ranges from 50 m to about 1 km in length.

Some small Melt Bodies, 5 to 30 m across, occur scattered in the Gray Member and are not common in the Black Member. These bodies are also lens-shaped

or irregularly shaped. Dike-like apophyses, some with flow lines and some appearing similar to fluidal-textured glasses, protrude from some of the Melt Bodies up to 30 m into the adjacent Gray Member. Locally discontinuous dikes up to 1 m thick, not observed to be connected to any Melt Body, intrude the Gray or Black Members (*see* section on Dikes).

The Melt Bodies are generally massive, amygdaloidal, and fine grained, are locally spherulitic, and commonly contain inclusions of country rocks up to 80% by volume (Photos 7.9 and 7.10), although some Melt Bodies contain < 5% inclusions. The matrix weathers rusty brown and is dark grey on fresh surfaces. Locally, Melt Bodies are medium to coarse grained and display acicular actinolite crystals, up to 6 mm long, which are particularly visible in weathered rinds (Photo 7.11). The acicular actinolite may be grouped in the form of well-developed rosettes each consisting of about 24 needles radiating from a central point (Photo 7.12). Small rock and mineral inclusions less than a few cm in diameter may be present, but there is no indication that they have partly disintegrated as there is with the fragments in the Basal Member matrix. Some small blebs of sulphide minerals < 5 mm in diameter are locally present. These blebs consist of various proportions of pyrrhotite, chalcopyrite, and pyrite.

Many Melt Bodies consist of 2 parts, a crystalline core and a chilled margin. Based on their mineralogy, the cores, which constitute the larger proportion of each Melt Body, can be distinguished as:

1. siliceous
2. feldspathic
3. granophyric

On the basis of their textures, the margins can be described as:

1. massive
2. flow-banded
3. brecciated

The chilled margins of the Melt Bodies range in width from several cm to a few m. The margins are foliated where the rocks have been tectonically deformed as in the South Range. The massive variety is very fine grained and dark grey on fresh surfaces. The flow-banded variety is green to greenish-grey, is commonly amygdaloidal, and is similar in appearance to the fluidal glass fragments found in both the Gray and Black Members. Where observed, this variety appears to have a sub-horizontal or moderately inclined attitude in contrast to that of the main part of the body. The brecciated variety consists of closely packed 'glassy' fragments which have distinct green and grey colour banding.

Inclusions

Most of the inclusions in any given Melt Body are very well sorted by size. The overall range is from 1 cm to 1 m across, but in some Melt Bodies, most fragments have a diameter of only a few cm.

The presence of abundant country rock inclusions 2 to 64 mm in diameter is a characteristic feature of many Melt Bodies. Any given Melt Body core contains a proportion of evenly distributed inclusions. The crystalline cores commonly contain 20 to 60% inclusions, whereas the chilled parts contain 1 to 5%.

Shapes of the inclusions in a given Melt Body range from rounded to subrounded to angular. Some inclusions are irregularly or slab-shaped and some appear bent.

The inclusions in the Melt Bodies are similar in terms of rock types and mineral characteristics to fragments in the Basal Member. The variety of metasedimentary inclusions in some Melt Bodies that lie within the Gray Member is significantly greater than the variety of such inclusions in Melt Bodies which occur within the underlying Basal Member, particularly in the South Range. On the North Range, granitic and gneissic fragments are less abundant in some Melt Bodies than in the Basal Member. On the South Range, gneissic fragments are relatively uncommon, but granitic fragments are more common in the Melt Bodies than in the Basal Member.

Large blocks of country rocks occur locally as inclusions entirely in the Melt Bodies, partly in the Melt Bodies, and partly in the adjacent Gray Member or Basal Member. Most of the largest blocks are up to 100 m long and are oval. Some blocks are irregularly shaped and are penetrated by the enclosing Melt Body. Collectively, these blocks consist of: quartz arenites, arkoses, equigranular and porphyritic granitic rocks, quartz-muscovite metasedimentary rocks, complex blocks of gneiss with bands of gabbroic rock and pyroxenitic lenses, and protobreccia (*see below*). Some dark grey, coarse-grained, quartz arenite is interbedded with conglomeratic layers, up to several cm thick, which are cut by very fine grained, dark grey to nearly black, pseudotachylite-like veins.

Of particular interest is a large irregularly shaped block of breccia (at least 130 m long) in a Melt Body cluster in Dowling Township east of High Falls. The breccia consists of quartz arenite, arkose, granitic, and rare, small, amphibolitic fragments in a fine- to medium-grained, homogeneous, quartzofeldspathic, granular matrix. These fragments of basement rocks account for 10 to 20% by volume, and have a shape similar to basement fragments in the Basal Member. The rock has been referred to as protobreccia (Peredery 1972a). Smaller blocks of protobreccia up to 2 m diameter are conspicuous because of their grey colour,

subrounded shape, and abundance (40%). Fragments of protobreccia < 64 mm long also occur in the Melt Bodies. The protobreccia is somewhat similar to breccias with low and high fragment populations in the Basal Member of the South Range (Table 7.2) in that both consist largely of quartz arenite fragments, but they differ in the size of the fragments or the degree of roundness of the fragments.

Some of the granitic and arkosic inclusions in the Melt Bodies have patches and stringers of igneous-textured material, similar to patches and stringers in the Basal Member, truncated by the Melt Body matrix.

Rare quartz arenitic or arkosic and granitic inclusions in the Melt Bodies have conical structures which are similar to the shatter cones commonly found in some rocks outside the Sudbury Structure (Dietz 1964). Many inclusions in the Melt Bodies display shock-metamorphic features (French 1967, 1972; Peredery 1972a).

Matrix

The crystalline core of Melt Bodies consists largely of fine- to medium-grained plagioclase, potassic feldspar, clinopyroxene, and quartz, and is of 3 varieties; siliceous, feldspathic, and granophyric (Table 7.3; Photos 7.13 to 7.15). The quartz content of the siliceous variety ranges between 27 and 51%, whereas in the feldspathic variety it ranges between 3 and 23%. The plagioclase content in the feldspathic variety ranges between 61 and 75%, or nearly double that in some of the siliceous or granophyric varieties. The micrographic intergrowth in the granophyric variety ranges between 8 and 44%, whereas in the other varieties, it is either weakly developed or absent. The

mafic mineral content among the 3 varieties ranges between 8 and 29%.

In many bodies, clinopyroxene is largely or completely altered to actinolite and/or chlorite. Most of the crystalline matrices are massive and have either anhedral to subhedral crystals or anhedral and highly interlocking crystals in the form of a crude graphic intergrowth (Photos 7.13 and 7.15). Locally, patches with a well-developed, very fine micrographic intergrowth are present (Photo 7.13). In some bodies, the crystals are partly aligned, suggesting flowage.

Both plagioclase and clinopyroxene, or their altered equivalents, tend to be long and prismatic (Photo 7.14), with some sheaf-like and radiating patterns also present, as in the devitrified chilled margins. The plagioclase generally ranges from 0.2 to 0.5 mm long laths, is commonly albitized, and has associated secondary epidote, some of which has allanite overgrowths. The clinopyroxene is fine grained, needle-shaped, and is generally altered in the North Range; in the South Range, where the rocks are highly deformed, it is completely altered to amphibole, biotite, and chlorite. Minor brown amphibole is present as anhedral crystals in the matrix or within quartz-bearing amygdules.

Potassic feldspar and quartz are fine-grained, interstitial minerals. Quartz may be in optically continuous patches up to 4 mm long or be intergrown with feldspar to produce a micrographic-like texture. In some cases, quartz has rod shapes similar to some quartz crystals with similar habit in the Basal Member (Photo 7.14). Accessory minerals include ilmenite and titanite or leucoxene, apatite which commonly occurs as needles, and equigranular zircon. Ilmenite is present as anhedral grains and/or small needles (Photo 7.13).

TABLE 7.3: MODAL DATA FOR CRYSTALLINE MELT BODIES.

	SILICEOUS MELT BODIES	FELDSPATHIC MELT BODIES	GRANOPHYRIC MELT BODIES
Plagioclase (and epidote)	32.0-56.0%	61.0-75.2%	35.8-57.7%
Quartz	27.6-50.9%	3.3-22.4%	6.7-11.8%
Perthite and/or micrographic intergrowth	tr.-1.3%	tr.-3.5%	8.5-44.0%
Pyroxene and/or amphibole + chlorite	8.5-22.0%	11.0-28.6%	8.3-17.0%
Stilpnomelane (alteration after pyroxene)	—	—	tr.-8.6%
Opaque minerals, (ilmenite)	tr.-1.6%	tr.-1.8%	tr.-1.7%
Titanite, (leucoxene)	tr.-0.2%	tr.-0.2%	tr.-0.3%

tr. = trace quantity
Data from Peredery (1972a)

The massive chilled margins consist of a felsic groundmass with clinopyroxene crystallites occurring in a variety of patterns such as radial, plumose, parallel, pleated, and herringbone. This suggests some of the groundmass may originally have been glassy. The crystallites are commonly altered to amphibole or chlorite. In chilled margins with coarser textures, the groundmass consists of plagioclase laths up to 0.5 mm long with interstitial quartz commonly forming sheaf-like, spherulitic, and pleated patterns. In some cases, the devitrified groundmass consists of a micrographic-like intergrowth of very fine grained feldspathic material and quartz. The mafic crystallites which are clinopyroxene or are an altered equivalent such as actinolite or chlorite, have a prismatic habit and commonly occur in sheaf-like or spherulitic patterns.

The flow-banded variety consists of microcrystalline devitrified material with flow lines defined by various proportions of mafic microcrystallites and very fine granules of mafic minerals in a felsic groundmass.

Fragments of the chilled margin in the brecciated variety have vague outlines and consist of clinopyroxene or actinolite, plagioclase, and quartz. The textures are very fine grained, and granular. There is generally some evidence of original flow banding, as in the flow-banded variety, which has been largely obliterated by fine-grained recrystallization.

Amygdules are more common in the chilled margins than in the crystalline parts and consist of quartz $\pm$ amphibole $\pm$ chlorite $\pm$ epidote. The amygdules tend to be elongate parallel to chilled margins in the flow-banded variety, whereas they tend to be spherical in the massive variety. Locally, some carbonaceous material is present in the amygdules as in some Melt Bodies at High Falls in Dowling Township. Sulphide minerals in the amygdules are not common and include pyrrhotite, chalcopyrite, marcasite, and uncommonly exsolution lamellae of pentlandite in pyrrhotite. Sphalerite and galena are extremely rare.

Mineral and microscopic rock inclusions < 3 mm across are common in the matrix of Melt Bodies (Photos 7.13 to 7.15). These inclusions range from sub-rounded to irregularly shaped. The minerals, which may be xenocrysts, include quartz, feldspar, and rare apatite and zircon. Most microscopic rock inclusions are quartzofeldspathic, but there are also mafic clots (inclusions?) composed of clinopyroxene or amphibole. Quartz is more abundant in the matrix surrounding quartzose inclusions than farther away. The mineral and rock inclusions are generally recrystallized, but some are cryptocrystalline and appear to have been plastically deformed. The similarity of the small mineral and rock inclusions to the larger inclusions in the Melt Bodies suggests that they are derived from these inclusions. Quartz inclusions commonly have a mafic reaction rim of amphibole or clinopyrox-

ene (Photo 7.15). Some of the quartz grains have relicts of shock-metamorphic planar elements.

GRAY MEMBER

The Gray Member is a continuous major unit of breccias ranging from about 200 to 700 m thick (see Figure 7.1). The member is locally underlain by granophyres of the Sudbury Igneous Complex, by Melt Bodies, or most commonly, by the Basal Member. Contacts between the Gray Member and these units are sharp. The Gray Member is overlain by the Black Member and the contact is locally sharp or gradational.

The Gray Member comprises many different breccia units which collectively have a much greater lithological variety than the units of the Black Member. The breccias are commonly grey to greenish grey on fresh surfaces. The breccias occur as varieties of Types 4, 2, and 3, in this decreasing order of abundance. Fragments of breccia similar to the Basal Member occur locally in the Gray Member in both Ranges. Figure 7.4 shows a generalized section through the Gray Member. Many of the individual breccia units appear to have limited lateral continuity. Some have a sharp contact with the adjacent unit (Photos 7.16 and 7.17), and some have gradational 'contacts' over a few cm to a few m.

In many cases though, the relationship is unclear due to incomplete exposure, and the breccias can be mapped, from outcrop to outcrop, by type only. The varieties of types of breccia are too numerous to describe individually, but Table 7.4 gives features of some examples based on units that are mappable on a small scale. The relationships between some units in part of Capreol Township, were outlined by Muir (1982) and are shown in Figure 7.7 (see p. 150). The following observations were made:

1. contacts are continuously traceable for short distances, commonly < 10 m
2. contacts are straight to irregular and locally units dip away from the centre of the Sudbury Basin by about 45° to 50°
3. most units are discontinuous
4. units may change considerably in apparent thickness
5. some breccias with similar lithological characteristics are found at various localities along strike within the Gray Member
6. the amount of potassic feldspar increases upward in the section
7. no planar bedding was observed within individual units of breccia of the Gray Member

The matrix colour in breccias of the Gray Member is varied. Well weathered surfaces are light brown to rusty brown, recently weathered surfaces (for ex-

TABLE 7.4: DESCRIPTIONS OF SOME BRECCIAS IN THE GRAY MEMBER, ONAPING FORMATION.

TYPE	SUPTYPE ¹	RELATIONSHIP	PROMINENT CHARACTERISTICS
4	a	a-b: not determinable	40% fragments of banded fluidal-textured material containing numerous crystal fragments; subrounded to subangular; 4 to 25 mm diameter
4	b	(upper) stratigraphic succession	25% quartz arenite and arkose fragments; subrounded to subangular; 6 to 20 mm diameter
4	c	(lower) b-c: sharp contact	55% to 60% pinkish brown weathering fragments of glass with white rims; subrounded; 2 to 5 mm diameter
2	a	commonly at or near top of Gray Member	25% to 30% fragments of composite breccia, granitic rocks, and arenites; many coated in fluidal-textured material; subrounded to subangular; 0.2 m to 1 m diameter
2	b	within Gray Member	30% to 35% fragments of granitic rocks, arenites, and fluidal-textured material; subrounded to rounded; 7 cm to 25 cm diameter
3	a	isolated occurrences	60% to 65% fragments of potassic, vesicular glass; subangular; 3 to 10 mm diameter
3	b	isolated occurrences	55% to 60% fragments of quartz arenite, arkose, and granitic rocks (subrounded to rounded), and fluidal-textured fragments (subrounded to subangular); 20 to 30 mm diameter

¹Letters distinguish different examples described here and are not used elsewhere in the text.

ample, those without a rind) are greenish grey to greyish green, and fresh surfaces are darker shades of grey, greenish grey and greyish green. The overall outcrop colour may be dominated by the matrix colour or the colour of the predominant fragments. Localized alteration, particularly around some Melt Bodies, has resulted in a light-green or grey, bleached matrix in the Gray Member. Glass fragments are also altered to white, beige, or pink feldspars and chlorite.

The lower part of the Gray Member tends to have a grey to greenish grey matrix largely because of pale green actinolite. The breccias have undergone considerable recrystallization so that some rock fragments are difficult or almost impossible to discern from the matrix. The matrix of the upper part of the Gray Member is greyish green to dark green because of actinolite and/or chlorite and tends to be less recrystallized than the lower part. Locally within the upper part of the Gray Member (for example see Figure 7.7), some units are more altered (recrystallized) than the units which underlie them. Minor carbonate minerals may be present in the matrix. Minor irregularly shaped patches of calcite-chlorite, chlorite-actinolite, or actinolite are locally present. These patches may be filled vugs. Schandl (1982) and Schandl *et al.* (1982) reported that feldspars in the glass and country rock fragments in the Gray Member specimens analyzed by them are predominantly albite (An_2 to An_3). Locally, there is some intermediate microcline (compare with Black Member). The upper 1/3 or more of the Gray Member generally contains significant potassic feldspar.

The Gray Member is generally similar in the North and South Ranges except for the tectonic over-

print in the South Range. The most notable differences are:

1. Units of Type 2 breccia commonly found forming the upper part of the Gray Member in the North Range are largely absent in the upper part of the Gray Member in the South Range.
2. The Gray Member, northwest of Bailey Corners in Garson Township, has several units and blocks of breccia not found in the Gray Member in the North Range.

The units and blocks of breccia in Garson Township are exposed continuously up to 100 m along their length and appear to be up to 700 m long (see Map 2491, back pocket). The units locally contain abundant blocks of quartz arenite and arkose up to 25 m across and are similar to breccias in the Basal Member. Blocks of breccia up to 6 m across that are similar to the above units are locally present in this area. The Gray Member in this part of the Sudbury Basin has been moderately to strongly sheared. The units and blocks of breccia may be tectonically emplaced slices of the Basal Member. Elsewhere, in western Garson Township, there are a few lenses, up to 40 m thick, of breccia similar, but not connected, to the Basal Member breccia. The lenses trend parallel to the tectonic fabric in the area, but are weakly deformed compared to the lenses of breccia near Bailey Corners.

General descriptions of the types of breccia of the Gray Member, in decreasing order of abundance, are given in the following accounts. The varieties of fragments which comprise these types of breccia are briefly described following the section on the Black Member.

Type 4 Breccias

Type 4 breccias (see Figure 7.2) constitute about 85 % of the Gray Member and are the most variable. Distinguishable units form discontinuous lens-shaped bodies which range from highly heterolithic to relatively monolithic (Photo 7.18) and from matrix-supported to fragment-supported (Photo 7.19). Locally, several units have been defined by sharp contacts (Photos 7.20 to 7.22), however, in most cases, units of Type 4 breccia have not been delineated by contacts.

Locally, there are large fragments of quartz arenite, arkose, or granitic rocks up to 20 m in diameter. Fragments > 64 mm across include assorted country rocks, fluidal-textured material, composite breccias, and plastically deformed siliceous rocks. Most fragments range from 1 cm to 0.5 m in diameter and are erratically distributed. In some localities, large lenses of Type 4 breccia occur in which the predominant fragment type accounts for up to 70 % of the breccia and is moderately to well sorted by size and shape.

Fragments from 2 to 64 mm across include all types of country rocks, plus various mixtures of simple and complex felsic glasses, composite breccias, microbreccia, and sulphide minerals; these fragments are listed in decreasing order of abundance.

The matrices of Type 4 breccias consist mostly of particles < 2 mm across which include mineral and lithic fragments derived from the above types of fragments. Up to 30 % of a matrix consists of irresolvable particles.

There are many varieties of Type 4 breccia which occur throughout parts of the Gray Member (see Table 7.4). One variety is characterized by 30 % of small, white, subrounded to subangular, simple felsic glass fragments that are in a medium to dark greenish grey, fine-grained matrix. A second variety is characterized by up to 20 % of pink granitic, arkose, and siltstone fragments, from 2 to 64 mm across with various shapes, contained in a dark greyish green matrix. A third variety is characterized by 25 % of small, subangular to angular, greenish grey glass fragments which have continuous, thin, white rims and lie in a greenish-grey matrix.

As well as the above Type 4 breccias, other breccias exist that are specific to one or a few locales. Some varieties include:

1. a breccia with a dark grey, siliceous matrix and ill-defined, medium to dark grey, siliceous fragments (located just south of Joe Lake)
2. a breccia with a medium grey matrix, and numerous, banded, beige, fluidal fragments, from 2 to 64 mm across, located in southwest Morgan Township (Figure 7.8)
3. a compacted greenish-grey rock with numerous flattened, complex, and simple 'glass' fragments (Photo 7.23)



Figure 7.8. Tracing of hand specimen from the Gray Member showing salient textural features of a locally present, medium grey breccia consisting of many light grey, fluidal-textured fragments some of which are composite fragments. Morgan Township. Fragments with tight diagonal lines are dark grey and aphanitic in hand specimen. Unpatterned fragments are quartz arenite. Fragments < 3 mm across are not shown.

Type 2 Breccias

Type 2 breccias constitute 5 to 10 % of the Gray Member. There are several varieties of this breccia, but only one can be associated with a particular stratigraphic position, that being at or near the top of the Gray Member. Where this breccia is present, Type 2 breccia may also constitute the basal part of the Black Member (see Figure 7.4). Locally, the breccia grades abruptly into, or is in sharp contact with, Type 4 breccia.

The main variety of Type 2 breccia is the most complex of all the breccias. It contains large fragments which range from 0.1 to 2 m in diameter, are subrounded to rounded, and consist, in approximate decreasing order of abundance of: quartz arenite, arkose, granitic rocks, composite breccias, plastically deformed siliceous rocks, and fragments of any of the above rock types coated in fluidal-textured material (Photo 7.24).

The matrices of Type 2 breccias are comparable to Type 4 breccia matrices (compare with Figure 7.3). Each Type 2 breccia unit in the Gray Member, however, has a different matrix. Some of these matrices have a great variety of rock types as fragments from 2 to 64 mm across, whereas other matrices contain fragments of the same size consisting of a few rock types.

Type 3 Breccias

Type 3 breccias constitute 10 to 15 % of the Gray Member. The most common variety of Type 3 breccia has 75 % by volume of fragments ranging from 15 to 25 mm across. Fragments ranging from 2 to 64 mm are well sorted in any unit of Type 3 breccia. Except for the

above features, Type 3 breccias are very similar to Type 4 breccias, and commonly are directly associated with these breccias in ill-defined zones. Some of the Type 3 breccias, however, form discrete lensoid bodies.

RELATIONSHIP BETWEEN THE GRAY AND BLACK MEMBERS

The contact between the Gray and Black Members has been previously described as "transitional" over a horizontal distance of about 10 to 70 m (Peredery 1972b; Muir 1981). The transition between the 2 members is marked by an abrupt increase in carbon content in breccias which locally contain chloritized shard-like fragments (Peredery 1972a). Peredery also noted that this is the first "stratigraphic horizon" to contain chloritized shards.

Muir (1983) noted that the black matrix (colour caused by carbon particles), does not define the Black Member *per se*. Muir (1982)³ described a sharp contact between the Gray and Black Members in Capreol Township which marks the lower limit of the horizon rich in chloritized shard-like fragments (see Figures 7.7 and 7.9; Photos 7.25 to 7.27). At this contact, and for the 3 m overlying it, the rock has very little carbon and is grey, not black. The black colour abruptly becomes apparent up-section. Feldspars across the contact change from albite and subordinate microcline in the Gray Member unit to orthoclase and subordinate albite in the Black Member unit (E.S. Schandl, Geologist, personal communication, 1983).

Three hundred m along strike to the southeast (see Figure 7.7), the black rock containing chloritized shard-like fragments is underlain by a black rock which has considerably different lithological properties (fragment type, shape) and no chloritized shard-like fragments (Figure 7.10; Photos 7.28 and 7.29). The black colour of this underlying unit gradually disappears within 15 m down-section. In the 2 examples of the contact described above, the rocks without the chloritized shard-like fragments are different varieties of Type 4 breccia (contrast Figures 7.9 and 7.10).

In this chapter, the Black Member is defined lithologically as constituting those units above, and including, the horizon rich in chloritized shard-like fragments⁴. This horizon, although present around most of the Sudbury Basin, is locally absent, in which case the contact between the 2 members is difficult to determine. Locally within the Black Member, breccias may have no chloritized shard-like fragments.

BLACK MEMBER

The Black Member is a continuous major unit of breccias around the Sudbury Basin, ranging from 800 to 1200 m thick (see Figure 7.1). The breccias are commonly black to dark grey. The member is underlain by the Gray Member and the contact is locally sharp or gradational. The Black Member is gradationally and conformably overlain by fine-grained mudstone of the Onwatin Formation.

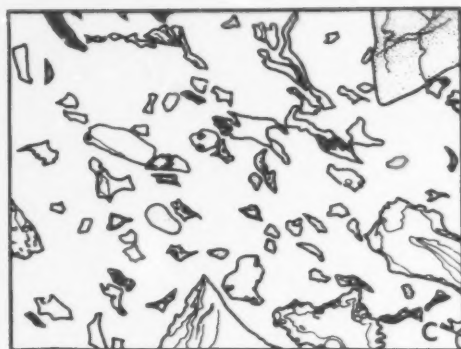
The Black Member consists of numerous breccia units which display less variety overall than the breccias of the Gray Member. The breccias occur as varieties of Types 4, 5, and 2 in decreasing order of abundance. Ill-defined lenses (fragments?) of breccia similar to some breccias in the Gray Member are locally present. Figure 7.4 shows a generalized section through the Black Member. Many of the individual units appear to have a limited lateral continuity, commonly less than several hundred m. Some have a sharp contact with the adjacent unit (Photo 7.30), but in many cases, the breccias change abruptly over a few cm to a few m. Generally, the relationship is unclear due to incomplete exposure and the breccias can be mapped from outcrop to outcrop by type only. Although the breccia units tend to fine overall upward in the section from Type 4 to Type 5 breccias, there is no consistent gradation except in the upper fifth of the member.

On a small scale, mappable units are present. Table 7.5 gives some examples of different varieties of breccia. Figure 7.7 shows examples of the relationship among some of the units of breccia.

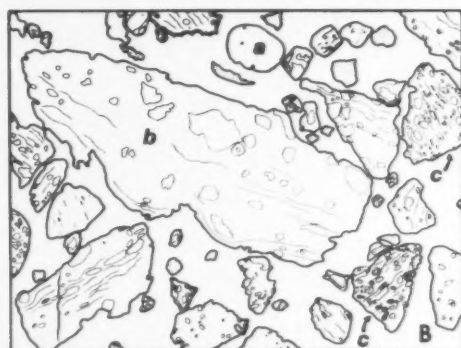
Well-developed planar bedding was recognized about 2/3 of the way up from the base of the Black Member in Lumsden Township (Photo 7.31). There, a 10 cm thick bedded unit traceable for 35 m, has an attitude of 135°, 25°SW (Muir 1983). The regional orientation of the Black Member there is 065°, 30°SE. The bedded unit is best defined on a weathered surface and consists of several poorly defined beds of fine, Type 4 breccia that range from 0.4 to 2.5 cm thick overlain and underlain by coarser Type 4 breccia. In thin section, larger, more rounded fragments in a very fine-grained matrix predominate in some beds, and smaller, shard-like, felsic fragments in a coarser matrix predominate in others. Both of the authors have located examples of conformable bedding within the lower 300 m of the member.

³The material in Muir (1983) was based on field work in 1981 and, although written first, was released after Muir (1982) which was based on field work in 1982.

⁴The views expressed in this sentence are those of one of the authors (T.L. Muir). The other author (W.V.P.) prefers to accept the base of the Black Member as being at the top of the horizon rich in chloritized shard-like fragments (see Discussions).



- C) Black Member; rock rich in chloritized shard-like fragments in a green-grey dense matrix (Photo 7.26).
- stippled: siltstone fragment
 - opaque: pyrrhotite
 - unpatterned: chloritized shard-like fragments
 - sub-parallel lines: complex glasses



- B) Gray Member; distinct unit of Type 4 breccia (Photo 7.27) in sharp contact with 'C'.
- stippled fragments are siltstone
 - a) single quartz crystal
 - b) complex felsic glass rich in xenocrysts and xenoliths
 - c) amygdaloidal and vesicular complex felsic glass



- A) Gray Members; distinct unit of Type 4 breccia in sharp contact with 'B'.
- fragments with sub-parallel lines: fluidal-textured glass
 - remainder of fragments: simple felsic glass with titanite crystals

Bar Scale ———

Figure 7.9. Tracings of part of 3 thin sections of Gray and Black Members showing salient textures and features. Samples were taken from the area shown in Figure 7.7; Capreol Township. Approximate distances between samples are: A to B = 50 m; B to C = 4 m. Stratigraphic topping is from A to C. Fragments < 1 mm across are not shown. Bar scale represents 2 mm.

Elsewhere, bedding occurs in the upper part of the Black Member, is poorly developed, and is part of the overall transition into the Onwatin Formation. Irregularly shaped lenses or patches of Type 3 or Type 5 breccia may be found within Type 4 breccia. The lenses or patches in the upper part of the Black Member consist of Type 5 breccia and are best observed in Morgan Township, and in Capreol Township north of Onwatin Lake. They dip toward the basin centre in Morgan Township (Williams 1957). Bedding in the above areas is uncommon, crudely developed, and disrupted. Near Onwatin Lake, lenses or fragments of Type 4 or Type 5 breccia may be found within Type 5 breccia; nearby, the reverse can be seen (Photo 7.32).

Lenses or patches in the lower part of the Black Member generally consist of Type 3 breccia. No well-developed planar bedding is apparent in the lower part.

Blocks of fine- to coarse-grained, black, Type 5 breccia (up to 1% in abundance) are irregularly distributed within the upper 2/3 of the Black Member, and are most abundant in the upper 1/3. These blocks are irregularly shaped, unoriented, unbedded, and some appear deformed. They range from 7 cm to 1.5 m long (Photo 7.33).

Overall, fragments of country rocks decrease in abundance in the Black Member, from about 15% at the bottom to < 1% at the top. However, they are irregularly distributed among individual units and may

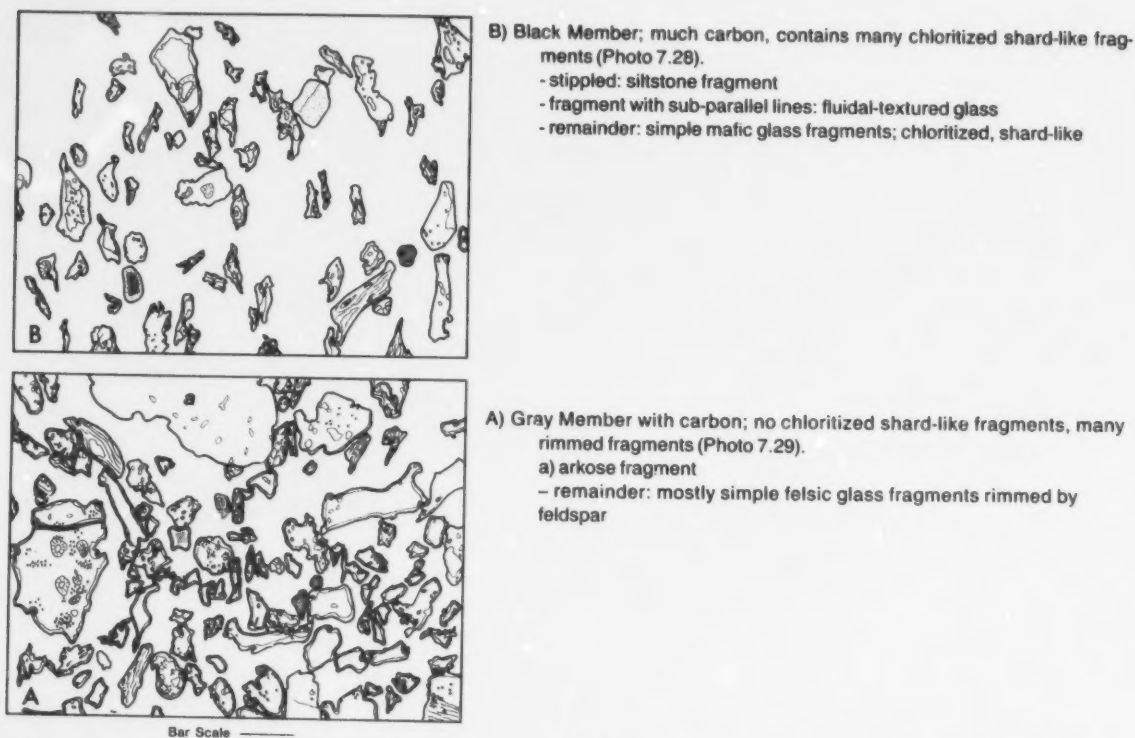


Figure 7.10. Tracings of part of 2 thin sections of Gray and Black Members showing salient textures and features. Samples taken from area shown in Figure 7.7; Capreol Township. Approximate distances between samples is 4 m. Stratigraphic topping from A to B. Fragments < 1 mm across are not shown. Bar scale represents 2 mm.

form up to 75% of some Type 3 breccias. Mafic shard-like fragments are the most abundant type of fragment, followed by fluidal-textured fragments and complex glass fragments.

Accretionary fragments (termed "mud balls", Peredery 1972b) are locally present in the lower half of the Black Member⁵. In one area, near High Falls in Dowling Township, they are fairly abundant. These fragments have a core consisting of a crystalline basement rock fragment or a glass fragment, or glass and lithic pieces < 2 mm in diameter. The accretionary fragments are oval or spherical, up to 5 cm in diameter, and are enveloped in finer material consisting of fine shard-like fragments and mineral fragments < 1 mm in diameter in an irresolvable matrix rich in carbon. These fine fragments tend to be aligned parallel to the outline of the core and may show a vague to distinct concentric layering with finer particles outward from the core. A similar feature was noted with other fragments in which fragments of country rocks or glass are surrounded by a thin zone of matrix defined by very

fine grained particles. The particles abruptly grade away from the fragment into the coarser matrix, and may be weakly aligned parallel to the outline of the fragment. These particular fragments are not accretionary.

The matrices of the Black Member breccias are medium to dark brown on well-weathered surfaces, are light to dark grey on recently weathered surfaces, and are black to medium grey on fresh surfaces. Much of the matrix consists of irresolvable particles. Carbon accounts largely for the colour of the Black Member matrices. Carbon content in samples analyzed by Burrows and Rickaby (1930) ranges from 0.20 to 0.58% and averages 0.39%. Stevenson (1972) reported values of up to 0.75%. Locally, areas within the Black Member have black, chloritized shard-like, fragments within a light grey matrix, indicating a low carbon content. Some bodies of Type 4 breccia within the Black Member have little or no carbon, and have a medium grey matrix. Other bodies have a light grey matrix and are unlike any of the surrounding, black breccias or any of the breccias of the Gray Member in terms of types or proportions of fragments (for example, unit 4i, near bottom left of Figure 7.7).

The Black Member is significantly less recrystallized than most of the Gray Member, with the excep-

⁵Note added in press: W. V. Peredery reported that similar features, but lacking fine carbon particles, have also been observed locally in the Gray Member.

TABLE 7.5: DESCRIPTIONS OF SOME BRECCIAS IN THE BLACK MEMBER, ONAPING FORMATION.

TYPE	SUBTYPE ¹	RELATIONSHIP	PROMINENT CHARACTERISTICS
4	a	lowermost part of Black Member	25% dark green to black, chloritized shard-like fragments; angular to subangular; 2 to 4 mm diameter
4	b	'b' is above 'c' by 3 m	30% to 35% fragments of various types (arenites, granitic rocks, glasses); subangular to subrounded; 10 to 25 mm diameter
4	c		40% fragments of fluidal-textured material and complex glasses; about half are highly potassic; subrounded to subangular; 2 to 10 mm diameter
5	a	towards upper part of Black Member	25% to 30% dark green to black, chloritized shard-like fragments angular to subrounded; < 2 mm diameter
5	b	irregularly shaped patches in 4a or 5a breccias	100% mixed light and dark particles (quartz, feldspar, chlorite, opaque minerals; < 1 mm diameter
2	a	at or near the lower part of the Black Member	20% to 25% fragments of arenites; granitic rocks, fluidal-textured material, and composite breccias; subrounded to rounded; 0.1 to 0.7 m diameter

¹Letters distinguish different examples described here and are not used elsewhere in the text.

tion of some units in the upper part of the Gray Member, particularly those which have some carbon in the matrix. Most of the mafic minerals in the Black Member are chlorite with local, subordinate actinolite. Locally in some units, many fragments have been altered to epidote-group minerals. Carbonate minerals are more common than in the Gray Member. Schandl (1982) and Schandl *et al.* (1982) reported that the feldspars in the 'glass' and country rock fragments in the Black Member are predominantly orthoclase and albite (An_2 to An_3), although albite is locally absent. These authors also reported that the albite is more disordered than in the Gray Member.

Type 4 Breccias

Type 4 breccias account for about 60% of the Black Member. On the average, the breccias tend to contain fewer and smaller fragments ranging from 2 to 64 mm diameter than the average Type 4 breccia of the Gray Member. Fragments > 64 mm across comprise quartz arenite, arkose, siltstone, granitic rocks, fluidal-textured material, composite breccias, and plastically deformed siliceous rocks. These fragments are similar to the same size fragments in the Gray Member and generally range from 0.1 to 0.3 m in diameter. Locally, there are rounded blocks of Type 3 breccia, up to several m in diameter, within Type 4 breccia.

Fragments ranging from 2 to 64 mm diameter consist of the above rock types, plus microbreccia, sulphide mineral fragments, and black, chloritized, shard-like fragments (Photo 7.34). These shard-like fragments are characteristic of much of the Black Member. Black siltstone fragments are noticeably more common in the Black Member than in the Gray

Member (Photo 7.26). Many of the felsic 'glass' fragments are either bluish green or are a milky, pale, opalescent blue. These 2 colouration types, accentuated by the black matrix, differ from those in the Gray Member which are white, beige, or pinkish brown.

The matrix of Type 4 breccias consists mostly of fragments < 2 mm in diameter, resembles a Type 5 breccia, and is generally black. Chloritized shard-like fragments are commonly found throughout the matrix. In one detailed cross-section examined in Capreol Township (see Figure 7.7), these shard-like fragments, which are moderately well sorted, grade in one unit from an average diameter of 3 to 0.5 mm over a horizontal distance of 75 m. This unit is overlain by a thin unit with numerous, potassic-rich 'glassy' fragments and a matrix with no visible shard-like fragments. The thin unit, in turn, is overlain by a unit bearing shard-like fragments which have an average diameter of about 2 mm and which decrease in size upward in the stratigraphy (Figure 7.11). Where chloritized shard-like fragments are not present, the matrix consists largely of complex glass fragments, quartz and feldspar crystal fragments, and small lithic fragments.

Type 5 Breccias

Type 5 breccias account for about 35% of the Black Member and occur as massive to poorly bedded discontinuous units forming lenses within Type 4 breccias in the upper few hundred m of the Black Member where it grades into argillites and slates of the Onwatin Formation. Type 5 breccias are also found as blocks of fine-grained material within Type 4 breccia in the up-

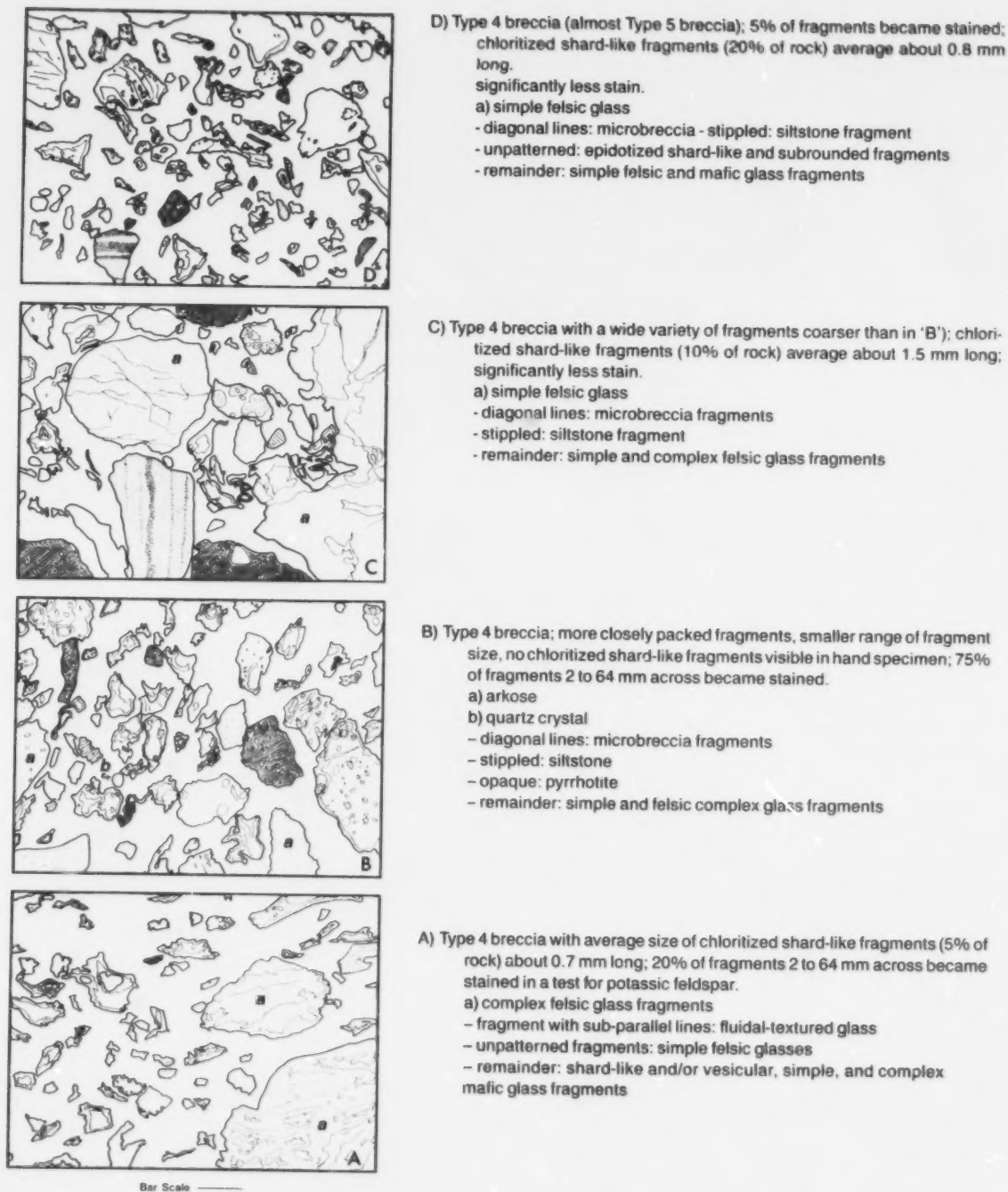


Figure 7.11. Tracings of part of 4 thin sections showing salient textures and features in successively overlying rocks which may be from different units. Samples were taken from the Black Member from the area shown in Figure 7.7; Capreol Township. Approximate distances between samples are: A to B = 18 m; B to C = 11 m; C to D = 10 m. Fragments < 1 mm across are not shown. Bar scale represents 2 mm.

per 2/3 of the Black Member, and as units or lenses within or between Type 4 breccia units.

The coarse-grained, Type 5 breccias have chloritized shard-like fragments and are similar to many fine-

grained, Type 4 breccias. Type 5 breccias from the upper part of the Black Member are fine grained and locally resemble some of the darker wackes of the Chelmsford Formation, particularly in Morgan Township (Rousell 1972; Muir 1983).

Type 5 breccias consist largely of various proportions of chlorite, quartz, plagioclase, carbonate, microcline, and sulphide minerals as crystal fragments or as lithic fragments. Much of the material is irresolvable under the microscope.

Type 2 Breccias

Type 2 breccias account for about 5% of the Black Member and occur in its lowermost part as discontinuous and locally ill-defined units. Many of these breccias are adjacent to Type 2 breccias in the uppermost part of the Gray Member. The breccias commonly grade into Type 4 breccia with a decrease in abundance of fragments > 64 mm across, both along strike and up-section.

The Type 2 breccia of the Black Member is similar to Type 2 breccias of the Gray Member in that it contains numerous fragments > 64 mm across composed of quartz arenite, arkose, crystalline basement rocks, composite breccias, fluidal-textured material, and fragments of these rocks coated by fluidal-textured material. The fragments are generally sub-rounded to rounded, show an overall range in diameter from 6.5 cm to 1.5 m, but usually range from 8 cm to 0.5 m in diameter. The matrix consists of fragments < 64 mm across and resembles a Type 4 breccia.

DIKES

Several vertical to sub-vertical dikes intrude the Gray and Black Members in Dowling Township (Peredery 1972a) and in Lumsden and Capreol Townships (Muir 1982, 1983). The dikes are exposed up to a length of 20 m and range from 10 to 25 cm in thickness. Contacts are sharp and the dikes have straight or zigzag trends. The dikes are commonly spherulitic throughout and have banding parallel to the dike margins. Some dikes contain wall rock inclusions. The continuity of banding and the proportion of spherules are highly variable within and among dikes. The interstitial material is aphanitic and greenish grey, with dark green patches. The spherules are grey to purple-grey and range from 2 to 4 mm in diameter (Photo 7.35). Minor amygdules are either chlorite-filled or quartz-filled. Altered, unidentified crystals occur in dendritic patterns and as sets of parallel crystals with different orientations. Quartz and feldspar crystals and crystal fragments may be present in minor amounts.

Burrows and Rickaby (1930) initially reported "dike-like masses" of spherulitic rock near Whitewater Lake in Snider Township. Thomson (1957) later described them as "short, stubby, disconnected bodies" one of which measured 9 m by 30 m. Another body is reported 0.5 km to the north of Whitewater Lake (J.M. Martins, Resource Geologist, Ministry of

Natural Resources, Sudbury, Ontario, personal communication, 1983).

A body at Whitewater Lake has dark grey spherules, up to 1 cm in diameter, which consist of radiating feldspar crystals and minor biotite and carbonate crystals. The spherules are separated by a black matrix consisting of fine-grained biotite with some chlorite. Some quartz-filled, amygdule-like structures up to 4 mm in diameter occur in the rock. The lack of complete exposure at this locality does not permit confirmation that these bodies are intrusions.

Locally in the South Range, there are slightly to moderately foliated amphibolitized gabbroic dikes up to 0.8 m thick which have intruded the Gray and Black Members. The dikes range from parallel to moderately discordant to the regional trend of the members. They are too small to show on the map (Map 2491, back pocket).

LITHOLOGY OF FRAGMENTS IN BRECCIAS OF THE GRAY AND BLACK MEMBERS

In this section, the essential fragment types are described. The fragments are divided into the following groups: country rock fragments which constitute crystalline basement rocks and metasedimentary rocks; microbreccia fragments; fluidal-textured fragments and bodies; devitrified glass fragments; composite fragments; crystals and crystal fragments; and sulphides and sulphide fragments. Some miscellaneous fragments are also briefly described.

Country Rock Fragments

The country rock fragments consist of Archean basement rocks and Proterozoic (Huronian) metasedimentary rocks. These fragments account for about 20 to 30% of the total volume of the Gray and Black Members. These fragments are discussed in geochronological order beginning with the oldest.

CRYSTALLINE BASEMENT FRAGMENTS

Crystalline basement fragments of Archean igneous and meta-igneous rock types found outside and in the vicinity of the Sudbury Structure occur in the Gray and Black Members. These fragments account for 20 to 40% of the country rock fragments, and 5 to 12% of the Gray and Black Members. The relative proportions of different types of fragments varies from locality to locality. Fragments of granitoid rocks are predominant amongst those from the crystalline basement and include granite, aplite, pegmatite, quartz monzonite,

granodiorite, and diorite. The granitoid fragments are generally beige to pink, and leucocratic. Microcline megacrysts are common. The fragments are generally subrounded to subangular, equidimensional to elongate in shape, and range from 0.1 to 1 m diameter. Some fragments are slabs up to 100 m long. The largest basement fragments tend to be in the lower part of the Gray Member and in the Basal Member.

In hand specimens, the appearance of the rocks ranges from 'normal' granitic to rocks that contain medium to dark grey quartz, translucent to clear feldspar and/or pink, semi-translucent feldspar. Freshly broken surfaces display quartz that appears frosted and feldspars that appear chalky. These minerals commonly have conchoidal fractures and tend not to break along cleavages. In large blocks, the translucent minerals occur in a rim up to 0.2 m thick.

Deformed lensoid patches comprising a streaky mixture of feldspar and quartz may be present. The fragments may also be moderately to strongly fractured.

Thin sections display a wide variety of textures ranging from 'normal' for a particular rock type (for example granite) to unusual. Also *see* description of unusual textures in section on Basal Member. Quartz is commonly recrystallized to a fine- to medium-grained mosaic texture or may have unrecrystallized patches with or without decorated planar features, a shock-metamorphic feature. Potassic feldspar, mostly microcline, has patches of cloudy brown alteration. Plagioclase is generally cryptocrystalline to microcrystalline and lies either within or beside patches of fine-grained altered or remnant plagioclase. The extremely fine-grained parts may show, by extinction orientation, bands which suggest that flow banding or plastic deformation took place (Photo 7.36). Spherulitic growths and planar lamellae may be present in the remnant primary plagioclase. Actinolite and/or chlorite are anhedral and partly altered. Minute opaque minerals may be concentrated as fine-grained disseminations in plagioclase or as recrystallized clumps of grains.

Gneissic rocks are the next most abundant and exhibit a poorly defined to well developed gneissosity and microscopic textures characteristic of the granitic fragments. More detailed descriptions of textures within granitic and gneissic rocks are given by French (1967, 1970, 1972) and Peredery (1972b). Quartz fragments of unknown source occur in minor amounts.

Fragments of mafic rocks such as amphibolite, metagabbro, and metadiabase are less abundant than the granitic or gneissic fragments and occur in approximately the same proportions as they occur in the basement. There are sparse metapyroxenite fragments. The metadiabase fragments which constitute porphyritic and massive varieties, are the least metamorphosed.

Most mafic fragments range from about 0.5 m in diameter to microscopic size. The larger fragments tend to be subrounded to rounded, whereas microscopic ones are subangular to subrounded. In one case, a 100 m long triangular block of porphyritic diabase was found in Morgan Township in the Sandcherry Creek area.

The mafic fragments commonly contain: clinopyroxene and/or orthopyroxene; actinolite or hornblende; biotite; chlorite; plagioclase, which has recrystallized to either small anhedral crystals, or to complex, very fine grained patches with patterns showing a sweeping or toroidal extinction; opaque minerals; and leucoxene. Fragments displaying the above features in feldspars commonly have pyroxenes showing reduced birefringence, kink banding, and unusual cleavage.

METASEDIMENTARY ROCKS

Metasedimentary fragments are generally considered to be derived from the Huronian Supergroup, even though it is not known whether post-Huronian sediments or sedimentary rocks were present when the Onaping Formation was deposited. The metasedimentary fragments account for about 60 to 80% of the country rock fragments observed on the South Range, but are less abundant on the North Range. These fragments comprise 12 to 25% of the Gray and Black Members.

The 2 most abundant types of metasedimentary fragments are quartz arenite and arkose. There are several varieties of each type in terms of mineral and matrix proportions, colour, and grain size. Many fragments are recrystallized, have ill-defined primary textures, and appear similar to fine-grained, equigranular, granitic rocks. The fragments may contain rounded pebbles of quartz, from a few mm to 40 mm long, which aids in determining their sedimentary origin. Fragments of quartz-sericite metasedimentary rocks are common in the South Range and have been noted in the North Range (Peredery 1972a).

Fragment shapes range from well rounded to rectangular and most fragments range in size from 1 cm to 1 m diameter. The overall range is from microscopic to at least 100 m long. Many of the largest blocks are sporadically fractured and/or internally brecciated. Some of the smaller fragments have a fractured, broken crust.

Large arenite fragments may exhibit sedimentary bedding. Sedimentary sequences of sandstone, siltstone, and granule conglomerate may be contained within a single block. Crossbedding (Thomson 1957; Stevenson 1961) and graded bedding (Peredery 1972a) are locally present. Some fragments show moderately to strongly deformed bedding. Others have broken

along undeformed bedding planes. Still other fragments have bedding that is subparallel to the length of the fragment, but that pinches in at the ends of the fragment.

In thin section, the arenite fragments display a wide variety of textures. Quartz and feldspar may or may not be recrystallized and may display shock-metamorphic features (French 1967; Peredery 1972a).

Matrices may be siliceous, feldspathic, or carbonate-bearing. Fragments of siltstone are uncommon within the Gray and Black Members. The fragments are more abundant in the Black Member, and generally range from 2 to 64 mm across, although rare fragments up to 1 m diameter locally occur. Most siltstone fragments are medium grey, dark green-grey, or black. These fragments are well bedded and moderately deformed to undeformed. Siltstone fragments tend to be darker coloured in the Black Member than in the Gray Member. They are darker than the matrix of the breccia. Some of the siltstone fragments are light greenish grey, similar in colour to some of the fluidal blocks, thinly laminated, highly fractured, and altered along the fractures (*see* also subsection on microbreccia fragments). In thin section, the fragments show thin to thick laminations, and are dense to semi-opaque.

Uncommon fragments of conglomerate range from 0.1 to 0.5 m in diameter and are found in the Gray Member (and Basal Member) within Type 2 breccia. Clasts in the conglomerate consist of varieties of quartz arenite and arkose in a siliceous matrix. The clasts are rounded to subangular, moderately well sorted, and range from 2 to 4 cm in diameter. Conglomeratic beds up to several 10s of cm thick occur within some large blocks of arkose.

SHOCK-METAMORPHIC FEATURES

Shock-metamorphic features are found in at least 10% of all of the varieties of country rock fragments in the Gray and Black Members. Many of these features have been partly altered by post-brecciation devitrification or recrystallization. The features include: small shatter cones (Peredery 1972b); planar features in quartz in up to 4 sets of parallel, straight lamellae or 'strings' of fluid and solid inclusions (French 1967); and planar features within plagioclase as parallel lamellae within twins (French 1967). French (1972) interpreted features in the Onaping Formation such as fracturing, crushing, and granulation of minerals, kinking of biotite, selective recrystallization of feldspar, plastic deformation of feldspar, recrystallization of quartz, and various stages of fusion represented by glass fragments and some biotite and titanite crystals as other evidence of various stages of shock metamorphism. Peredery (1972a) included partial melting of zircon as evidence of shock metamorphism.

One of the authors (W.V. Peredery) accepts French's interpretation as correct. Peredery points out that the vitrification of mineral grains without the homogenization of adjacent grains is much more easily accounted for as a result of vitrification in a solid state (maskelynite formation) associated with a shock wave than by normal volcanic processes. From his experience, he regards many of these features as unique to impact sites. The other author (T.L. Muir) points out that the positive identification of maskelynite or other diaplectic glasses is precluded in the recrystallized environment of the Onaping Formation and that features similar to many of those described by French have been observed in some volcanic rocks. Muir is, therefore, more cautious in accepting French's interpretation as a demonstration of shock, and remains unconvinced of the uniqueness of shock metamorphism to impact processes.

The most common established shock-metamorphic features are planar features in quartz that are decorated with very small inclusions. Within grains showing evidence of recrystallization, the decorated planar features are preserved preferentially in the central parts of crystals, especially within fragments of quartz arenite, arkose, and granitic rocks. Individual quartz crystal fragments are less prone to displaying decorated planar features. Remnants of undecorated lamellae are uncommon.

Microbreccia Fragments

Microbreccia (Peredery 1972a) occurs within the Gray and Black Members as subrounded fragments, ranging in size from microscopic to a few m in diameter, and as dikelets in fractured metasedimentary or granitic fragments. Microbreccia fragments account for only a minor proportion of the Onaping Formation and are more abundant in the Gray Member. Many of the fragments and veinlets resemble Sudbury Breccia of the North Range, and some resemble fluidal-textured material with crystal inclusions.

The microbreccia fragments have a dense, medium to dark grey or black matrix consisting of very fine grained irresolvable particles. Weakly to strongly developed, contorted banding may be present. Numerous quartz and feldspar crystal fragments as well as small quartzofeldspathic lithic fragments (up to a few mm in diameter) are scattered throughout the microbreccia and constitute up to 35% of the fragment (Photo 7.37).

The microbreccia veinlets, which are uncommon, are black to grey and occur in fragments of quartz arenite, arkose, and siltstone (Photo 7.38). The veinlets have an irregular trend, thickness, and distribution within the host rock fragment. The fragments within the veinlets consist of broken quartz and feldspar crystals, and country rocks. In at least one case, the micro-

breccia contains fragments with oval and shard-like shapes. The matrix is irresolvable under the microscope.

Sulphides and Sulphide Fragments

Sulphide mineral fragments^a are found in both the Gray and Black Members, but they are generally more abundant in the latter (Photo 7.39). The fragments range from < 1 mm to 2 cm long, are angular to subrounded, and consist of one or more of the following minerals: pyrrhotite, chalcopyrite, pyrite, and sphalerite in decreasing order of abundance. Some fragments consist of pyrrhotite with an incomplete rim of chalcopyrite.

Silicate rock fragments, and fluidal-textured and glass fragments that contain the same types of sulphide minerals in the same order of abundance as above, are more common than sulphide fragments. Williams (1957) remarked that the pyrite and pyrrhotite he observed tended to be within rock fragments (Photo 7.39). The most common rock fragments containing sulphide minerals are quartz arenite, quartz, and fluidal material although sulphide minerals are also found in some granitic and gabbroic basement rock fragments. The sulphide minerals occur as irregularly shaped patches within silicate rock fragments, and as patches, blebs, or streaks in the fluidal-textured and glass fragments.

Sulphide minerals are also found as blobs and irregularly shaped patches within the matrix of the Gray and Black Members, which in these cases makes their identification as fragments, replacement features, or vug fillings equivocal. Pyrrhotite or chalcopyrite may be found along hairline fractures in breccias that contain fragments or blebs of sulphide minerals.

Desborough and Larson (1970) noted pyrrhotite, chalcopyrite, pyrite, sphalerite, galena, and Ni-rich marcasite as disseminated grains and aggregates within or adjacent to fragments in the breccias. These authors also noted textures suggesting that nickel-marcasite and Ni-pyrite have replaced pyrrhotite in some cases.

Total sulphide content in the breccias is locally up to 5% (for example, southwest Morgan Township), but generally is much < 1% in the Gray Member, and up to 1% in the Black Member.

^aW. V. Peredery regards the majority of the sulphides described by T. L. Muir as primary sulphide fragments to be the consequence of secondary replacement of rock or glass fragments. T. L. Muir recognizes that local mobilization of sulphides has occurred in some cases, but considers that primary sulphide fragments are also present.

Fluidal-Textured Fragments and Bodies

Fluidal-textured material occurs within the Gray and Black Members as fragments and bodies that have flow banding ranging from weakly to well developed. This material was most likely glass in its original state, but is discussed separately from other glasses because of its occurrence as bodies and fragments. Some fluidal-textured material resembles other rock types and may have had a different origin.

The fluidal-textured bodies occur mostly in the lower part of the Gray Member, and in the lower 2/3 of the Black Member, within Type 4 breccia units. Other bodies are locally abundant in zones which parallel the outline of the Sudbury Basin, particularly within Type 2 breccia.

The fluidal-textured bodies range from a few m to about 30 m long, and are lensoid, angular and blocky, or irregular in shape. Some of the bodies, especially the larger ones, appear to be spatially associated with the Melt Bodies. Flow banding may be either conformable to the body or truncated at its margin. Thin apophyses of fluidal-textured material extend into the surrounding breccia for up to 0.3 m.

Fluidal-textured fragments consist of aphanitic, light greyish-green, greenish grey, or dark green dense material commonly with amygdule- and vesicle-like structures (Photo 7.40). In some bodies, these structures are spherical in the centre and oval or highly elongate within and parallel to the outer margin. Banding, defined by differences in colour, ranges from weak to moderately well developed and from undeformed to contorted. Individual bands are up to a few mm thick, but generally are < 1 mm thick.

Coarsely spherulitic fragments are uncommon. One fragment, 0.8 m by 0.5 m in size and virtually identical to the spherulitic dikes described in the subsection entitled Dikes, occurs with some composite fragments in the Black Member in northeast Fairbank Township.

Microscopic features of the fluidal-textured bodies are similar to the fluidal-textured glass fragments described below.

Fluidal-textured fragments range from microscopic size to about 1 m in diameter. In exposures, some of the fluidal-textured fragments are similar to the fluidal-textured bodies. In the Gray Member, the fragments are commonly greenish grey to greyish green, subrounded to angular, and display moderately well-developed to weakly developed banding. In the Black Member, the fragments are commonly greyish green to green, subrounded to angular, and variably banded. The fluidal-textured fragments range from aphanitic and massive to very fine grained with well-

developed flow banding. Banding tends to be disconformable to the outline of the fragment, that is the banding is truncated, in the more angular pieces, and conformable in the more rounded pieces. Many fragments of fluidal-textured material with truncated flow banding enclose fragments of country rocks. Fluidal-textured material with conformable banding may coat fragments of country rocks, breccias consisting of glassy and lithic fragments, and fluidal-textured material with complexly contorted and truncated banding (see section on Composite Fragments).

In thin section, the fluidal-textured fragments with weakly developed flow banding are extremely fine grained, dense, and consist of mafic minerals in a leucocratic groundmass. Banding is indicated by different colours (commonly shades of green), different mineral proportions, and different grain sizes. Flow banding ranges from about 0.5 to 3 mm thick. The fluidal-textured fragments may contain quartz and/or feldspar crystals and crystal fragments. Uncommonly, the quartz crystals show shock lamellae. Some quartz fragments are rimmed by very fine grained actinolite or chlorite. Amygdule-like structures of quartz or quartz and actinolite may be present.

In thin section, the fluidal-textured material with well-developed flow banding displays a variety of features. Strong colour banding is discontinuous and is generally defined by dark to light green actinolite and/or chlorite, colourless microcrystalline or very fine grained feldspathic or siliceous minerals, and strings of quartz and/or feldspar crystals (Photo 7.41). The bands are typically deformed around crystal fragments and lithic inclusions both of which rarely have shock lamellae. Recrystallized felsic streaks and bands may comprise parallel, stubby, anhedral to subhedral crystals of feldspar oriented perpendicular to the trend of the banding. Cloudy patches of very finely disseminated high-relief minerals are locally present: these minerals may include titanite, ilmenite, or leucoxene. Amygdule-like structures and spherulitic textures, where present, are erratically distributed within some felsic bands. The amygdule-like structures are filled with combinations of quartz, actinolite, or chlorite.

Glass Fragments

Various fragments can be interpreted as having been initially glass based on devitrification textures and morphology. The glass fragments range so widely in texture, mineral composition, colour, and degree of devitrification that it is difficult to develop a consistent, precise classification. For the convenience of a general description, the glasses have been subdivided into "simple glasses" with both felsic and mafic varieties; and "complex glasses" with varieties that are predominantly felsic or predominantly mafic. The primary division is based on the degree of complexity of

relict textures. "Felsic" and "mafic" refer to the overall present composition of the fragments with no implication regarding the original composition, or the processes of alteration from a glass to a mineral state.

SIMPLE GLASS FRAGMENTS

Simple glass fragments are those that have uncomplicated internal textures and are either monomineralic or nearly so. Many breccia units in the Gray and Black Members contain either one or both varieties of simple glass fragments. Table 7.6 gives characteristics of the simple glasses.

COMPLEX GLASS FRAGMENTS

Complex glass fragments (Peredery 1972b) consist of felsic and mafic minerals, and have complex or complicated internal textures. Some breccia units have complex fragments with a relatively restricted range of textures. In other units, numerous shapes and textures of complex fragments are present. Table 7.6 gives characteristics of the complex glasses.

Crystals and Crystal Fragments

The fluidal, glass, and composite fragments, as well as the fine-grained to very fine grained matrix of the breccia units in the Gray and Black Members contain sparse to numerous crystals and crystal fragments of quartz and feldspar, and uncommonly amphibole, biotite, and clinopyroxene (?). The origin of some of these crystals is equivocal.

Quartz crystals and crystal fragments range from < 0.1 to 2.5 mm in diameter and are present as:

1. subangular to rounded, poly-crystalline quartz fragments found within the lower 2/3 to 3/4 of the Gray Member
2. angular to subrounded, single or polycrystalline fragments, with minute inclusions, fractures, undulose (strained) extinction, and, rarely, shock-metamorphic features. These are found in the upper part of the Gray Member and in the Black Member.
3. well-rounded to rounded, single, clear, weakly strained, quartz crystals without shock-metamorphic features, and rarely with embayed outlines (Photo 7.42). These are heterogeneously distributed within the Black Member (up to 0.5% abundance), and in the upper Gray Member. These are commonly visible in hand specimens, particularly in some Black Member units, and look like black, vitreous, quartz 'eyes'. Some have been found in chloritized shard-like fragments (Muir 1981, 1983).

Feldspar crystal fragments range from 0.1 to 1.0 mm in diameter and consist of:

CHAPTER 7

TABLE 7.6: VARIETIES OF GLASS IN THE GRAY AND BLACK MEMBERS, ONAPING FORMATION.

FEATURE	SIMPLE GLASSES		COMPLEX GLASSES	
	FELSIC	MAFIC	FELSIC ^a	MAFIC ^a
Occurrence	—more abundant in Gray Member —second most abundant type of glass in Gray Member —common in breccias with numerous fragments of vesiculated felsic glass —pinkish fragments locally restricted to some units (mostly in Gray Member)	—1^c chloritized shard-like fragments most common glass within Black Member —2 actinolitized fragments in Gray Member —3^c erratically distributed in Gray Member, locally up to 1%; may be surrounded by white-weathering matrix	—almost 90% of composite glasses —most abundant type of glass in Gray Member	—least abundant variety of glass fragment —more common in Black Member
Colour (weathered)	—most are white to beige —some pale to deep pink, pinkish brown, brown	—1 black to dark green —2 dark green —3 dark green	—Gray Member—white to beige —Black Member—grey, bluish grey, opalescent blue	—green, dark green, white bands and patches
Textures	—vesicular —spherulitic —rimmed, unrimmed; axiolitic or segmented	—1 minor vesicles; some with feldspathic rim —2 massive, acicular crystals —3 massive to radiating acicular crystals; some have a 'shell' of subradiating crystals	—amygdaloidal; actinolite, chlorite, quartz —spherulitic, feathery, splaying feldspar —globular; discrete, rounded bodies of actinolite and/or chlorite —banding—various proportions of felsic and mafic minerals; generally discontinuous, some is due to collapsed elongate vesicles or felsic minerals of different composition —patches of mafic minerals irregularly distributed —rims of feldspar; continuous and discontinuous	—amygdaloidal; quartz, actinolite, locally carbonate —spherulitic; actinolite, chlorite —globular; discrete rounded bodies of very fine grained feldspar —banding—generally minor feldspar/quartz bands; some mafic bands with composition different from matrix —rims of feldspar; continuous, and discontinuous, less common than with felsic complex glass
Shape	—most subangular to angular; minor subrounded, or rectangular, or irregular and shard-like	—1 angular to subangular; most shard-like, some polygonal —2 subangular to subrounded; some shard-like —3 angular to rounded; generally subangular	—overall subrounded to rounded; irregularities due to broken vesicles or plastic deformation	—as with felsic complex glasses
Size	—generally < 2 cm	—1 < 1 mm to 10 mm —2 < 1 mm —3 generally 2 mm to 1 cm; overall 1 mm to 5 cm	—generally 5 mm to 2 cm; up to 5 cm	—generally 3 mm to 1.5 cm; up to 3 cm

TABLE 7.6: Continued

FEATURE	SIMPLE GLASSES		COMPLEX GLASSES	
	FELSIC	MAFIC	FELSIC ^a	MAFIC ^b
Mineral content	—mostly feldspar, quartz —chlorite, actinolite up to 25% of fragment; commonly in centre —rims—white or brown feldspar —spherules—feldspar —anhedral to euhedral titanite in chlorite/actinolite —epidote-group minerals replaced fragments locally in Black Member	—1 cryptocrystalline chlorite with sweeping extinction patterns; local cloudy patches of titanite —2 actinolite, minor chlorite —3 fine-grained acicular actinolite as masses or in patterns radiating from centre of fragment	—feldspar-albite and/or potassic feldspar (orthoclase in Black Member, microcline in Gray Member) ^c ; fine- to very fine grained, twinned and untwinned —actinolite and chlorite intergrown with feldspar but mostly at centre of fragment —locally sub-calcic augite ^d —locally euhedral titanite and monazite ^e (up to 1% in fragment) —locally specks or blebs of pyrrhotite, chalcopyrite	—Black Member—chlorite, actinolite —Gray Member—actinolite, chlorite —also feldspar, quartz, titanite
Reference photos	19, 22, 27, 34, 43, 47	22, 26, 28, 34, 42	19, 21, 22, 26, 27, 34, 37, 39, 43, 46, 48	19, 21, 26, 27, 37, 46, 48

Notes:

^aequivalent to feldspathic complex glasses (Peredery 1972a, 1972b)^bequivalent to green and dark green complex glasses (Peredery 1972a, 1972b)^cequivalent to black chloritized glasses (Peredery 1972a, 1972b)^dmay have originally been broken and unbroken megacrysts^eSchandl (1982); Schandl *et al.* (1982)^fPeredery (1972a, 1982b); based on composition from microprobe^gMuir (1981)

- angular to subrounded, anhedral to subhedral, plagioclase crystals that may be twinned and/or zoned, and are rarely bent or plastically deformed
- subangular to subrounded, anhedral to subhedral, potassic feldspar, with or without polysynthetic 'tartan' twinning

Two or 3 separate crystals of either type of feldspar may be found together. Williams (1957) also reported orthoclase, albite, and perthite crystals.

Lithic fragments consisting of fine- to medium-grained quartz, plagioclase, and potassic feldspar are assumed to be fragments of granitic rocks. Some have granophyric textures (Peredery 1972a).

Much less common than quartz or feldspar fragments are anhedral crystals of green amphibole which are < 0.5 mm in diameter. Rarely, 0.5 mm or smaller crystals which resemble green pyroxene are found. Rectangular, square, and triangular crystals or crystal fragments consisting of acicular actinolite were found in several thin sections (Photo 7.43). In one case, an

euhedral crystal of green biotite 0.3 mm long was found.

Composite Fragments

Composite fragments are defined here as fragments composed of more than one type of material, excluding country rock fragments (Muir 1981, 1982). These comprise fragments of breccia within breccia, fragments with more than one type of fluidal-textured material, fragments of glass within glass, or any combination of the above. Composite breccia fragments are found throughout the Gray and Black Members and are most common in Type 2 breccias. These fragments are found on the scale of outcrops (Photo 7.44, Figure 7.12), hand specimens (Photo 7.45, Figure 7.13), and thin sections (Photos 7.46 to 7.48).

Composite fragments may be complex. For example, a particular fragment in the Gray Member consists of:

- a 40 mm diameter, fluidal-textured, flow-banded fragment (containing sandstone fragments) within



Figure 7.12. Tracing of hand specimen showing salient textures and features of part of a composite block of relatively monolithic, light grey, Type 4 breccia which is within a Type 2 breccia at the upper part of the Gray Member; Trill Township. Banded fragments are fluidal-textured. Unpatterned fragments are simple felsic glass. Fragments < 2 mm across have not been drawn.

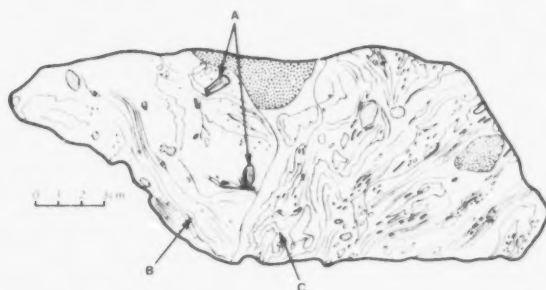


Figure 7.13. Tracing of hand specimen of part of a body or fragment of composite fluidal-textured material; from an outcrop of Type 2 breccia in the Gray Member, Capreol Township. Heavily stippled fragment is arkose. Dashed-line fragment is gabbro. Light-stippled fragments are quartz arenite.

- A) flow-banded fragment in 'B'
 B) fluidal-textured material with numerous small quartz and/or feldspar crystal 'fragments'; flow banding poorly developed and discordant to 'C'
 C) fluidal-textured material with well-developed, contorted flow banding

2. a 0.2 m diameter fragment of Type 4 breccia, which is
3. coated by fluidal-textured material with flow banding conformable to the breccia fragment
4. all of which lies within a Type 4 breccia unlike that which comprises the breccia fragment (that is, point 2 above)

A particular complex composite fragment in the Black Member consists of:

1. a 10 cm diameter fragment of very coarse arkose (containing fragments of finer quartz sandstone) which is
2. enclosed by fluidal-textured material with highly contorted flow lines truncated at the outer edge, which is

3. enclosed by faintly flow-banded, fluidal-textured material

4. all of which lies within Type 4 breccia

In thin section, some individual fragments have amygdules filled with material, consisting of particles < 2 mm across, which is different from the matrix of the breccia in which the fragment lies.

Miscellaneous Fragments

A variety of fragments not previously described accounts for much less than 1% of the Onaping Formation. They are subrounded to subangular and are generally < 2 mm in diameter (maximum 5 mm). The source and origin of these fragments has not been determined although some or all may be country rock fragments.

Examples of these miscellaneous fragments are:

1. closely spaced, fine-grained, twinned and untwinned, sub-parallel, feldspar laths in a brown, irresolvable matrix
2. very fine grained, unoriented, plagioclase needles, some with swallow-tail-like terminations, in a green-brown, irresolvable matrix
3. fine- to very fine grained plagioclase needles in a pyroxene or amphibole matrix
4. fine-grained, carbonate-bearing rocks, some of which contain oval, amygdule-like structures, and some of which are shard-like

PETROCHEMISTRY

Prior to 1970, only a dozen or so analyses of rocks from the Onaping Formation had been published (Burrows and Rickaby 1930; Sadler 1958). Since then, Stevenson (1972) gave data for a few analyses of the Gray and Black Members, Peredery (1972b) presented a plot of about 48 analyses of fluidal glass fragments and Melt Bodies, and Muir (1983) presented data and plots for several analyses of spherulitic dikes, fluidal-textured fragments, breccias, and what are presently called Melt Bodies.

Data presented in this chapter have not been published before. The analyses and diagrams are presented in Tables 7.7 to 7.14 and Figures 7.14 to 7.17.

The Basal Member matrix specimens included a variety of textures, but small fragments of country rock were excluded as much as possible. Melt Body specimens were chosen to be virtually inclusion free. Duplicate analyses for major oxides indicate the Melt Bodies are fairly homogeneous on a hand specimen scale (Peredery 1972a). The analyses of Gray and Black Member specimens are from whole rocks of relatively fine-grained breccias chosen to exclude as

many notable fragments of country rocks as possible on the scale of a hand specimen. Analyses for rocks outside of the Sudbury Structure have been presented because fragments of these rocks occur in the Onaping Formation. These are plotted on the particular triangular plots for the purpose of comparison. Data are derived from: Card (1965, 1968); Collins (1936); Fairbairn and Robson (1942); Ginn (1961); Grant *et al.* (1962); Meyn (1973); Muir (1983); and Speers (1957).

Microprobe analyses of feldspars in the Basal Member and Melt Bodies were done for individual crystals in the matrices, feldspathic clots or inclusions, and igneous-textured patches and stringers. Microprobe analyses of pyroxenes in the Basal Member and the Melt Bodies were done for individual grains and clusters of grains in the matrices. No evidence of zoning in pyroxenes was obtained either from the microprobe results (Peredery 1972a) or from petrographic observations. Microprobe analyses of fluidal-textured glasses exclude any obvious rock and mineral inclusions and were taken from fragments that had no obvious alteration other than recrystallization.

The cation diagram presented in Figure 7.14 is used for comparison of one group to another and does not infer a preferred origin by the authors. Figure 7.14 shows that:

1. The patterns of data for individual groups range from elongate (for example, Basal Member) to subcircular (for example, Black Member).
2. There is an overall progression from a felsic to mafic composition up-section in the Onaping Formation (Figure 7.14a, b + c, d, e) for the 4 major subdivisions of the Onaping Formation, although there is some overlap between adjacent subdivisions.
3. Nearly all specimens of the Onaping Formation, except those of the Black Member, have chemical compositions comparable to calc-alkalic rocks.

Analyses of the Basal Member matrix show a moderate spread of points in Figure 7.14a and are evenly split between fields comparable to calc-alkalic dacite and calc-alkalic andesite. The analyses of some quartz arenite fragments from the Basal Member (South Range) show a greater spread.

Most analyses from Melt Bodies lie within the field that is comparable to calc-alkalic andesite (Figures 7.14b, and 7.14c) and fewer analyses fall into the calc-alkalic basalt field. Two analyses of Melt Body samples are distinct from the main group of samples (Figure 7.14b) and are considered to be altered (Peredery 1972a). Most analyses of whole rock specimens of Gray Member breccias lie within a fairly well defined group in the calc-alkalic basalt field (Figure 7.14d) although some overlap into the tholeiitic basalt field. The analyses of whole rock specimens of Black

Member breccias are tightly grouped and lie almost entirely within the tholeiitic basalt field (Figure 7.14e).

Microprobe analyses of fluidal glasses (Figure 7.14f) show a wide distribution related to relatively constant iron plus titanium to magnesium ratios for various proportions of aluminum (Figure 7.14f) or alkalis (not shown). About 40% of these fluidal fragments have a normative nepheline component (Peredery 1972b). No Melt Body analysis does.

The majority of the fluidal-textured bodies and fragments, and spherulitic dikes fall within the field comparable to calc-alkalic basalt (Figure 7.14g) as do the Gray Member specimens.

The samples of granophyres from the upper part of the Sudbury Igneous Complex overlap the tholeiitic and calc-alkalic fields (Figure 7.14h). Most of the samples that lie on the calc-alkalic side are compositionally similar to andesite.

Analyses of rocks outside of the Sudbury Structure are spread throughout a broad area in the tholeiitic and calc-alkalic fields. A few are comparable to komatiitic rocks (Figure 7.14i).

Figure 7.15a shows that microprobe analyses of feldspar crystals, in both the Basal Member and the Melt Body matrices plot in the albite-orthoclase field with some compositions almost pure albite and orthoclase. Most of the Melt Body feldspars analyzed are albite (Figure 7.15a). Feldspars in the igneous-textured stringers are comparable to feldspars in the Basal Member matrix.

Figures 7.15c and 7.15d indicate that many of the clinopyroxene crystals from the matrices of the Basal Member and Melt Bodies, and from the igneous-textured patches and stringers are essentially similar in composition. Some of the clinopyroxene crystals from the plagioclase-rich granophyre are also similar but others have a higher proportion of iron (*compare with* Peredery and Naldrett 1975). The clinopyroxenes in Figure 7.15c and 7.15d are more magnesian and lower in iron than those in the normal granophyre (*compare with* Naldrett *et al.* 1970). The field defined by clinopyroxene crystals of the Melt Bodies is broader than that of the Basal Member and overlaps with part of the clinopyroxene field of the mafic and felsic norites (*compare with* Peredery and Naldrett 1975; Hewins 1971) and the Contact Sublayer (*compare with* Hewins 1971). The petrographic characteristics of the pyroxenes in the Basal Member matrix and the igneous-textured stringers resemble those in the matrix of the Melt Bodies.

Melt Body compositions (whole rock) and fluidal-textured glass compositions (microprobe) are plotted in Figure 7.16 in terms of FeO/MgO versus (Na₂O+K₂O)/MgO, and CaO/MgO versus

TABLE 7.7: CHEMICAL ANALYSES OF BASAL MEMBER MATRIX SPECIMENS, ONAPING FORMATION.

SAMPLE REFERENCE NUMBER	1	2	3	4	5	6	7	8	9	10
Major Oxides and Volatiles ^a										
SiO ₂	69.30	67.10	65.40	66.40	68.00	66.30	69.30	65.70	68.70	72.20
TiO ₂	0.62	0.67	0.64	0.69	0.51	0.62	0.60	0.56	0.70	0.72
Al ₂ O ₃	12.60	13.50	16.10	15.50	14.40	15.70	13.50	15.90	13.20	11.80
Fe ₂ O ₃	5.70	6.26	4.27	4.07	3.93	3.59	4.85	3.98	3.45	4.26
FeO ^b										
MnO	0.08	0.10	0.03	0.05	0.04	0.04	0.10	0.04	0.05	0.06
MgO	2.57	2.86	1.88	2.04	1.79	1.66	2.45	1.93	2.43	2.03
CaO	1.17	1.40	3.36	2.69	1.64	2.27	1.40	3.55	1.94	1.09
Na ₂ O	2.75	3.14	5.05	5.21	3.68	4.53	2.93	4.60	4.09	3.78
K ₂ O	3.05	2.97	1.08	1.48	3.57	2.89	2.80	1.67	3.40	1.40
P ₂ O ₅	0.02	0.04	0.03	0.02	0.03	0.04	0.02	0.04	0.02	0.0
CO ₂	0.37	0.46	0.05	0.10	0.40	0.11	0.10	0.20	0.07	0.50
S	0.11	0.07	0.01	0.06	0.03	0.06	0.10	0.02	0.01	0.01
Total	98.34	98.57	97.90	98.31	98.02	97.81	98.15	98.19	98.06	97.85
LOI ^c	1.90	1.90	1.00	1.30	1.30	1.10	1.60	1.20	0.90	1.80
Sp.Gr. ^d	2.67	2.66	2.73	2.71	2.65	2.68	2.70	2.69	2.68	2.68
Trace Elements ^e										
Au	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ba	960	1040	420	980	1420	2120	1000	760	1560	330
Be	2	2	1	1	1	1	2	1	2	2
Co	14	16	11	11	8	10	14	12	10	13
Cr	83	98	45	59	63	39	71	60	78	83
Cu	44	38	5	20	24	24	50	22	< 5	< 5
Li	15	16	9	8	11	10	17	8	6	8
Mo	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Nb	7	8	< 1	< 1	13	< 1	1	< 1	7	< 1
Ni	38	36	21	26	32	24	43	23	46	55
Pb	15	11	< 10	< 10	< 10	< 10	85	< 10	< 10	10
Pd	1	< 1	< 1	< 1	3	< 1	1	< 1	2	< 1
Pt	2	2	< 1	< 1	4	< 1	4	< 1	3	< 1
Rb	80	80	50	60	100	120	80	60	100	50
Sc	7	8	4	1	9	1	5	4	9	5
Sr	180	210	430	290	160	430	285	465	195	95
V	80	85	60	55	70	50	70	60	80	75
Y	10	11	4	2	12	2	8	4	11	5
Zn	118	82	24	36	23	29	50	31	19	72
Zr	160	160	85	50	140	105	150	100	160	125

(Na₂O + K₂O)/MgO. The plots show a clustering of the points of both the Melt Bodies and fluidal-textured glasses. The clustering shows a distinct elongation in terms of the total alkalis to magnesia ratio. Within the individual samples, this elongation is even more pronounced as shown by points joined by dashed lines.

Figure 7.17 illustrates some variations in the Gray and Black Members in terms of whole rock compositions for specific elements and properties as a function of distance up-section from the Gray Member/Basal Member contact. Some of the consecutive samples show a reasonably linear relationship. The largest changes are directly associated with specific mappable units separated by sharp contacts. The Al₂O₃ has a bimodal distribution. The TiO₂ increases from the lowest to highest values over 5 consecutive samples and decreases over 5 other consecutive samples. The Na₂O

and K₂O have a well-defined antipathetic relationship throughout the sampled section and show marked consistent trends in the lower part of the section. The Co shows a somewhat erratic distribution but also reveals an increase over 6 consecutive samples and a decrease over 5 consecutive samples.

The normative plagioclase index (Irvine and Baragar 1971) shows, with one exception, a general increase in the Gray Member over 7 consecutive samples. The differentiation index (Thornton and Tuttle 1960; a measure of a rock's "acidity", useful in establishing differentiation trends) shows a general, but non-linear, decrease from samples 3 to 9 and from 11 to 16 (except for sample 15; see figure caption). Specific gravity shows sharp changes corresponding to known contacts, and correlative changes across suspected contacts.

TABLE 7.7: CONTINUED

SAMPLE REFERENCE NUMBER	11	12	13	14	15	16	17	$\bar{x}^1$	σ^1
Major Oxides and Volatiles ^a									
SiO ₂	78.70	78.10	72.70	71.94	92.00	86.80	87.30	74.19	8.35
TiO ₂	0.49	0.56	0.70	0.44	0.35	0.31	0.39	0.59	0.14
Al ₂ O ₃	10.60	8.47	12.00	12.18	4.30	7.23	5.86	3.77	1.97
Fe ₂ O ₃	2.25	4.44	3.54	0.94	0.82	0.61	1.60	3.96 ^a	1.84
FeO ^b				2.98					
MnO	0.03	0.09	0.05	0.09	0.02	0.02	0.03	0.06	0.04
MgO	1.21	3.16	2.13	1.09	0.61	0.29	1.25	2.02	0.97
CaO	0.31	0.41	1.09	0.82	0.26	0.96	0.12	1.59	1.14
Na ₂ O	3.33	1.73	4.90	2.02	0.38	1.92	0.31	3.26	1.51
K ₂ O	2.14	1.07	1.19	4.76	0.32	0.46	0.98	2.08	1.25
P ₂ O ₅	0.0	0.02	0.02	0.0	0.0	0.0	0.0	0.03	0.01
CO ₂	0.08	0.11	0.23	0.02	0.14	0.10	0.12		
S	0.02	0.02	0.01	n.d.	0.01	0.02	0.04	0.04	0.03
Total	99.16	98.18	98.56	97.28	99.21	98.72	98.00		
LOI ^c	0.70	1.90	1.20	1.34	0.80	0.50	1.30		
Sp.Gr ^d	2.66	2.68	2.69	n.d.	2.63	2.67	2.66		
Trace Elements ^a									
Au	< 2	< 2	< 2	n.d.	< 2	< 2	5		
Ba	560	220	200	n.d.	70	330	170	756	565
Be	1	1	2	n.d.	< 1	1	1		
Co	8	14	10	n.d.	< 5	6	< 5	11.7	3.4
Cr	61	93	67	41	13	60	5	64.4	28.3
Cu	6	12	< 5	n.d.	8	14	8	21.6	14.3
Li	7	12	13	n.d.	< 3	6	< 3	10.5	3.6
Mo	< 10	< 10	< 10	n.d.	10	< 10	< 10		
Nb	< 1	< 1	< 1	n.d.	< 1	< 1	< 1	7.7	4.0
Ni	19	66	35	n.d.	25	33	< 5	35.8	13.4
Pb	< 10	< 10	< 10	n.d.	10	12	55		
Pd	< 1	1	< 1	n.d.	< 1	< 1	30		
Pt	< 1	3	< 1	n.d.	3	< 1	85		
Rb	80	40	60	n.d.	< 10	10	20	64	30
Sc	1	3	3	n.d.	1	< 1	1	4.7	3.1
Sr	70	60	95	n.d.	30	65	40	196	143
V	40	60	60	n.d.	16	13	25	59	25
Y	< 2	6	6	n.d.	4	2	2	6.5	4.2
Zn	22	56	28	n.d.	17	23	34	45.9	32.5
Zr	105	130	155	n.d.	80	90	110	121	34

Samples: ^a1 to 9: matrix; North Range^a10 to 13: matrix; South Range^a14: matrix^a15 to 17: fragments in Basal Member

Notes:

^a uncorrected weight percent^a total Fe as Fe₂O₃ where blank^c loss on ignition^d specific gravity^e Au, Pd, Pt as ppb; all others as ppm^f Data normalized to be volatile free; $\bar{x}$ = mean, σ = standard deviation^g Total Fe as Fe₂O₃ for all samples^h Muir (current research); chemical analyses by Geoscience Laboratories, Ontario Geological Surveyⁱ Peredery (1972a), Table 8

n.d. not determined

CHAPTER 7

TABLE 7.8: CHEMICAL ANALYSES OF MELT BODY SPECIMENS (SET A), ONAPING FORMATION.

SAMPLE REFERENCE NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13
Major Oxides and Volatiles ^a													
SiO ₂	64.31	65.08	68.72	69.50	62.51	61.99	68.38	67.33	67.61	60.91	61.27	68.00	68.82
TiO ₂	0.58	0.56	0.48	0.47	0.62	0.61	0.47	0.49	0.49	0.65	0.69	0.49	0.48
Al ₂ O ₃	14.09	13.81	12.40	11.98	14.76	14.51	12.48	12.95	12.74	14.42	14.94	12.94	12.78
Fe ₂ O ₃ ^b	1.87	1.53	1.20	1.57	2.39	2.34	1.47	2.10	1.84	2.82	2.07	n.d.	1.30
FeO ^c	4.14	4.17	3.41	3.01	2.95	4.39	3.63	3.59	3.65	4.12	5.15	4.52	3.41
MnO	0.17	0.15	0.15	0.17	0.19	0.16	0.12	0.15	0.13	0.15	0.17	0.12	0.12
MgO	3.71	3.73	3.47	3.88	3.87	3.77	2.51	2.74	2.98	3.87	4.31	2.57	2.31
CaO	4.28	2.66	2.12	2.19	3.54	2.74	2.33	1.72	1.71	4.48	2.95	2.15	2.08
Na ₂ O	3.40	3.70	3.19	2.55	5.33	4.41	3.03	2.81	2.56	3.31	3.12	2.75	3.45
K ₂ O	2.26	2.60	2.52	3.08	0.51	2.09	3.27	3.23	3.51	2.33	1.42	2.40	2.55
Total	98.83	98.01	97.67	98.42	96.69	97.03	97.70	97.13	97.24	97.08	96.11	95.96	97.32
LOI ^c	1.40	1.60	1.40	1.40	1.10	1.60	2.20	2.20	2.00	2.40	2.90	2.30	2.00
Co ^d	.002	.002	.001	.001	.001	.003	.009	.009	.007	.007	.008	0.02	0.006
Cr ₂ O ₃ ^e	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02
Ni ^e	.004	.004	.001	.004	.001	.006	.005	.005	.005	.005	.005	.005	0.005

SAMPLE REFERENCE NUMBER	14	15	16	17	18	19	20	21	22	23	24	σ ^d	σ ^e
Major Oxides and Volatiles ^a													
SiO ₂	69.16	69.46	67.20	67.15	63.03	70.11	69.60	68.49	64.60	68.34	67.69	68.55	2.90
TiO ₂	0.49	0.49	0.48	0.50	0.62	0.50	0.50	0.49	0.59	0.56	0.54	0.55	0.07
Al ₂ O ₃	12.81	12.81	12.46	12.02	13.60	13.27	13.32	13.00	13.69	12.92	12.80	13.61	0.90
Fe ₂ O ₃	1.39	1.43	n.d.	n.d.	2.40	0.80	1.10	1.39	1.04	1.09	1.34	1.69	0.56
FeO ^b	3.11	2.78	2.74	2.91	3.50	2.91	2.74	2.95	4.44	3.91	4.09	3.70	0.71
MnO	0.11	0.09	0.10	0.12	0.23	0.08	0.08	0.08	0.12	0.11	0.12	0.14	0.04
MgO	2.18	2.12	3.40	3.91	3.94	1.63	1.66	2.41	2.84	2.43	2.53	3.12	0.82
CaO	1.66	0.73	3.42	3.88	4.02	2.01	2.36	1.47	1.51	0.58	0.54	2.45	1.14
Na ₂ O	3.31	2.63	8.50	7.20	3.99	2.90	3.54	3.65	3.21	3.30	4.06	3.85	1.44
K ₂ O	2.91	4.47	0.37	0.28	1.01	3.08	3.06	3.70	4.18	2.73	1.95	2.55	1.15
Total	97.14	97.03	98.69	97.99	96.36	97.31	97.98	97.65	96.24	95.99	95.68		
LOI ^c	2.00	2.00	1.30	1.10	2.00	1.30	1.30	1.70	2.90	2.00	2.40		
Co ^d	0.014	0.006	0.013	0.006	0.013	0.006	0.005	0.010	0.007	0.008	0.007		
Cr ₂ O ₃ ^e	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02		
Ni ^e	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005		

Samples: 1 to 24: Peredery (1972a), Table 21

Notes:

^a uncorrected weight percent

^b FeO determined by wet chemical analysis; Fe₂O₃ calculated

^c loss on ignition

^d Data normalized to be volatile free; $\bar{x}$ = mean, σ = standard deviation

n.d. not determined

SUMMARY

The Onaping Formation comprises complex, stratified breccia units and igneous-textured bodies that in some ways are unique, and in some ways are similar to other rock units found on Earth. The authors have endeavoured to describe the significant characteristics of

the formation as these are currently known, but further work will inevitably lead to recognition of additional features. The Onaping Formation is critical to an understanding of the Sudbury Structure and it is hoped that this chapter has contributed to that end.

TABLE 7.9: CHEMICAL ANALYSES OF MELT BODY SPECIMENS (SET B), ONAPING FORMATION.

SAMPLE REFERENCE NUMBER	1	2	3	4	5	6	7	8	9	10	11
Major Oxides and Volatiles ^a											
SiO ₂	70.20	69.00	68.70	66.30	61.80	68.20	67.20	68.70	66.90	64.80	68.10
TiO ₂	0.67	0.65	0.77	0.78	0.81	0.47	0.47	0.77	0.74	0.80	0.64
Al ₂ O ₃	12.50	12.30	12.00	12.80	14.70	14.50	14.90	12.70	12.10	12.70	12.20
Fe ₂ O ₃	4.89	6.19	6.58	6.91	8.07	0.80	1.10	3.94	8.36	5.58	5.62
FeO ^b						3.00	2.75				
MnO	0.06	0.11	0.12	0.14	0.12	0.06	0.07	0.09	0.13	0.09	0.07
MgO	2.73	2.67	3.33	3.51	3.75	2.55	2.65	3.70	3.61	4.36	3.03
CaO	1.33	1.32	0.97	1.61	4.12	2.62	2.22	2.21	2.32	2.92	2.44
Na ₂ O	3.57	2.40	2.17	3.22	3.20	3.68	3.72	5.32	2.58	4.90	3.91
K ₂ O	2.60	2.60	2.22	2.75	2.12	1.66	1.50	0.84	0.26	0.36	1.77
P ₂ O ₅	0.0	0.01	0.01	0.04	0.05	0.06	0.07	0.02	0.01	0.03	0.02
CO ₂	0.07	0.10	0.11	0.18	0.23	0.15	0.15	0.12	0.41	0.27	0.09
S	0.02	0.02	0.04	0.10	0.19	0.01	0.01	0.01	0.04	0.01	0.02
H ₂ O ⁺	n.d.	n.d.	n.d.	n.d.	n.d.	1.37	1.13	n.d.	n.d.	n.d.	n.d.
H ₂ O ⁻	n.d.	n.d.	n.d.	n.d.	n.d.	0.44	0.50	n.d.	n.d.	n.d.	n.d.
Total	98.84	97.37	97.02	98.34	99.16	99.57	98.44	98.42	97.46	96.82	97.91
LOI ^c	1.20	1.70	2.30	1.90	1.20	1.70	1.90	1.20	2.50	2.40	1.20
Sp.Gr. ^d	2.69	2.69	2.70	2.72	2.76	2.69	2.70	2.70	2.73	2.71	2.76
Trace Elements ^a											
Au	< 2	< 2	< 2	3	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ba	590	640	720	860	1280	250	380	230	90	120	580
Be	1	2	2	2	2	n.d.	n.d.	2	2	2	2
Co	17	15	15	19	25	13	16	15	25	15	19
Cr	109	96	88	106	154	100	90	123	101	122	107
Cu	6	29	32	38	43	< 5	6	7	26	< 5	24
Li	14	19	20	22	16	14	21	10	20	24	9
Mo	< 10	< 10	< 10	< 10	< 10	n.d.	n.d.	< 10	< 10	< 10	< 10
Nb	1	6	10	9	11	n.d.	n.d.	6	< 1	6	5
Ni	41	38	37	69	71	27	36	49	92	54	47
Pb	18	400	11	3080	400	< 10	< 10	59	< 10	< 10	< 10
Pd	< 1	1	< 1	3	2	n.d.	n.d.	< 1	3	< 1	1
Pt	< 1	< 1	2	5	3	n.d.	n.d.	1	4	< 1	3
Rb	100	70	70	30	80	90	60	20	< 10	10	40
Sc	6	8	9	8	11	n.d.	n.d.	9	4	9	8
Sr	95	195	125	205	320	180	260	120	45	75	155
V	90	85	90	105	135	n.d.	n.d.	105	100	115	95
Y	8	13	12	13	13	20	20	10	9	11	13
Zn	27	62	60	48	42	28	47	24	39	26	32
Zr	150	155	155	180	180	140	130	160	135	165	145

TABLE 7.9: CONTINUED

SAMPLE REFERENCE NUMBER	12	13	14	15	16	17	18	19	20	$\bar{x}^1$	σ^1
Major Oxides and Volatiles ^a											
SiO ₂	65.80	68.80	60.60	63.70	70.40	76.40	68.60	73.60	72.70	69.47	3.77
TiO ₂	0.75	0.62	0.81	0.81	0.81	0.47	0.55	0.43	0.60	0.69	0.14
Al ₂ O ₃	15.20	12.00	13.60	13.70	12.00	11.90	12.90	11.20	12.40	13.19	1.17
Fe ₂ O ₃	3.78	5.16	7.74	7.44	5.03	2.74	6.08	4.51	4.20	5.68 ^a	1.62
FeO ^a											
MnO	0.07	0.10	0.18	0.14	0.07	0.03	0.05	0.08	0.06	0.09	0.04
MgO	2.87	2.64	5.66	3.95	3.07	1.10	2.98	2.58	2.61	3.24	0.93
CaO	3.89	2.70	5.11	3.49	0.87	0.66	1.86	2.00	0.67	2.31	1.23
Na ₂ O	4.66	3.43	1.45	2.09	4.05	1.80	3.49	2.56	3.91	3.38	1.07
K ₂ O	1.22	2.47	2.74	2.87	0.97	3.76	2.03	1.88	0.82	1.92	0.95
P ₂ O ₅	0.05	0.04	0.06	0.07	0.05	0.0	0.02	0.01	0.01	0.04	0.02
CO ₂	0.73	0.12	0.14	0.19	0.73	0.19	0.07	0.20	0.16		
S	0.01	0.02	0.15	0.09	0.01	0.04	0.01	0.08	0.01	0.05	0.05
H ₂ O +	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		
H ₂ O-	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		
Total	99.03	98.10	98.24	98.54	98.06	99.09	98.64	99.13	98.15		
LOI ^b	1.70	1.20	2.30	1.60	2.30	0.80	0.90	1.10	1.40		
Sp.Gr. ^c	2.73	2.71	2.85	2.80	2.66	2.67	2.73	2.72	2.68		
Trace Elements ^a											
Au	< 2	< 2	< 2	< 2	< 2	< 2	4	< 2	< 2		
Ba	840	580	650	510	180	260	390	500	190	492	299
Be	2	1	2	2	1	3	2	1	1		
Co	8	13	19	20	15	12	17	11	11	16.0	4.4
Cr	37	101	171	131	98	61	107	83	85	103.5	29.2
Cu	14	17	36	48	5	< 5	< 5	36	5	23.3	14.9
Li	6	9	16	18	8	6	10	9	7	13.9	5.9
Mo	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10		
Nb	3	< 1	7	7	< 1	< 1	< 1	< 1	< 1	6.5	2.9
Ni	12	36	58	50	34	13	40	19	42	43.3	19.5
Pb	< 10	< 10	< 10	84	< 10	< 10	< 10	13	12		
Pd	< 1	< 1	1	1	< 1	< 1	3	< 1	< 1		
Pt	< 1	2	3	3	< 1	< 1	9	2	2		
Rb	40	70	80	110	40	100	80	60	10	61	31
Sc	10	6	10	9	5	< 1	6	5	4	7.5	2.2
Sr	200	200	240	255	75	90	150	135	45	151	77
V	110	90	160	115	85	40	95	75	80	98.3	25.2
Y	12	7	10	13	3	8	8	8	3	9.7	3.2
Zn	28	40	107	215	42	42	28	48	52	51.9	42.7
Zr	165	140	120	115	160	170	155	125	130	150	19

Samples: ^a 1 to 5, 8 to 10: North Range^a 6, 7: North Range^a 11 to 20: South Range

Notes:

^a uncorrected weight percent^a total Fe as Fe₂O₃ where blank^a loss on ignition^a specific gravity^a Au, Pd, Pt as ppb; all others as ppm¹ Data normalized to be volatile free; $\bar{x}$ = mean, σ = standard deviation^a total Fe as Fe₂O₃ for all samples.^aMuir (current research): chemical analyses by Geoscience Laboratories, Ontario Geological Survey^aMuir (1983), Table 7: chemical analyses by Geoscience Laboratories, Ontario Geological Survey

n.d. not determined

TABLE 7.10 CHEMICAL ANALYSES OF GRAY MEMBER (WHOLE ROCK) SPECIMENS, ONAPING FORMATION.

SAMPLE REFERENCE NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Major Oxides and Volatiles*															
SiO ₂	62.40	68.50	63.90	63.00	63.30	64.70	62.90	68.40	62.40	66.90	61.60	71.70	65.60	66.60	60.10
TiO ₂	0.72	0.68	0.80	0.77	0.79	0.92	0.83	0.80	0.83	0.94	0.94	0.51	0.89	0.85	0.84
Al ₂ O ₃	13.10	12.10	12.50	12.40	13.20	12.70	11.80	12.30	13.10	12.30	12.40	10.10	12.30	12.10	12.20
Fe ₂ O ₃	7.88	5.05	7.89	7.30	6.41	4.92	7.06	4.02	6.11	5.96	7.68	4.30	6.76	6.20	8.80
MnO	0.19	0.07	0.17	0.17	0.14	0.12	0.12	0.07	0.10	0.09	0.14	0.09	0.09	0.08	0.15
MgO	3.95	3.37	4.33	5.50	5.55	4.89	5.27	3.82	4.60	3.71	4.81	4.39	3.79	3.88	5.68
CaO	4.65	2.57	3.52	3.22	3.59	4.07	4.05	2.72	3.48	1.42	3.50	2.61	2.23	1.87	4.25
Na ₂ O	3.37	3.76	3.15	5.24	4.89	5.55	5.24	5.58	6.58	3.10	4.63	3.66	3.79	3.31	5.40
K ₂ O	1.73	1.92	1.44	0.10	0.35	0.56	0.38	1.20	0.33	2.40	2.16	1.72	2.39	2.52	0.86
P ₂ O ₅	0.06	0.01	0.05	0.04	0.04	0.04	0.04	0.03	0.05	0.03	0.06	0.02	0.02	0.02	0.06
CO ₂	0.17	0.24	0.14	0.14	0.16	0.60	0.06	0.20	0.37	0.10	0.20	0.17	0.07	0.09	0.15
S	0.19	0.01	0.03	0.01	0.01	0.01	0.02	0.13	0.04	0.01	0.02	0.01	0.06	0.07	0.05
Total	98.41	98.28	97.92	97.89	98.43	99.08	97.77	99.27	97.99	96.96	98.14	98.68	97.99	97.59	98.54
LOI ^b	1.40	1.50	2.00	1.50	1.80	1.20	1.40	1.10	1.40	1.80	1.80	1.10	1.50	1.50	1.50
Sp.Gr. ^c	2.83	2.72	2.76	2.76	2.75	2.75	2.79	2.72	2.74	2.72	2.76	2.72	2.73	2.71	2.79
Trace Elements*															
Au	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	2	<2	<2	<2	<2
Ba	530	400	710	30	110	150	100	330	100	1000	500	470	840	1380	180
Be	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Co	16	16	19	14	16	11	14	17	14	18	17	7	22	20	18
Cr	132	118	116	16	135	117	113	123	130	114	114	69	124	117	125
Cu	44	5	28	8	8	5	6	17	8	13	10	20	300	52	12
Li	12	4	12	9	10	7	7	6	8	16	8	7	15	12	10
Mn	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Nb	8	3	10	11	11	10	11	2	8	10	16	6	9	10	11
Ni	36	40	50	54	48	54	57	53	44	47	50	53	46	45	54
Pb	<10	<10	15	186	95	168	56	<10	<10	<10	31	19	<10	<10	<10
Pd	<1	<1	<1	4	1	2	1	<1	1	<1	<1	<1	<1	<1	<1
Pt	<1	2	2	<1	2	2	2	<1	3	2	<1	1	2	1	2
Rb	50	60	30	<10	2	10	<10	30	<10	70	60	40	80	90	20
Sc	10	9	9	9	10	10	9	8	9	10	11	8	12	10	8
Sr	180	100	230	55	160	85	65	60	75	155	60	30	180	125	40
V	130	100	110	145	150	125	140	70	85	70	90	50	115	65	95
Y	14	15	12	12	11	13	16	9	12	12	16	13	13	16	13
Zn	77	23	116	33	31	20	26	16	20	31	30	20	30	30	30
Zr	160	150	160	160	170	160	150	150	155	155	150	115	135	140	145

TABLE 7.10: CONTINUED

SAMPLE REFERENCE NUMBER	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	$\bar{x}$	σ
Major Oxides and Volatiles ^a																	
SiO ₂	59.50	59.70	60.80	62.90	63.50	63.50	64.80	63.10	63.50	60.20	71.70	70.70	71.50	72.00	70.70	66.37	3.97
TiO ₂	0.94	0.77	0.70	0.84	0.72	0.92	0.67	0.63	0.66	0.80	0.65	0.56	0.64	0.39	0.54	0.77	0.15
Al ₂ O ₃	12.50	12.00	12.60	12.70	12.90	12.60	12.30	12.50	12.60	11.60	10.10	10.20	10.00	9.86	9.86	12.20	1.10
Fe ₂ O ₃ ^b	8.84	10.10	9.00	6.91	7.04	8.07	6.71	7.76	5.85	9.21	4.66	4.78	4.86	6.30	6.35	6.86	1.63
MnO	0.16	0.20	0.12	0.10	0.09	0.09	0.10	0.12	0.14	0.19	0.10	0.11	0.12	0.12	0.09	0.13	0.04
MgO	5.63	5.79	4.75	3.86	3.71	3.91	3.59	4.08	5.37	6.45	3.80	4.26	4.64	4.27	4.11	4.63	0.83
CaO	4.12	3.73	3.56	3.10	2.63	2.16	2.95	2.27	4.03	3.95	1.71	2.86	2.15	1.66	2.25	3.07	0.91
Na ₂ O	5.49	4.28	4.87	5.29	4.28	4.75	3.83	2.74	5.96	5.01	3.92	4.70	2.61	1.62	1.76	4.41	1.24
K ₂ O	0.59	0.74	1.50	1.75	2.77	0.97	2.50	3.61	0.20	0.24	0.65	0.21	1.60	2.25	2.80	1.44	1.01
P ₂ O ₅	0.07	0.06	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.05	0.02	0.03	0.01	0.0	0.01	0.04	0.02
CO ₂	0.09	0.24	0.22	0.29	0.18	0.16	0.56	0.54	0.35	0.16	0.40	0.20	0.12	0.21	0.18		
S	0.02	0.03	0.25	0.25	0.30	0.08	0.43	0.35	0.02	0.01	0.01	0.01	0.01	0.0	0.29	0.10	0.13
Total	97.95	97.64	98.42	98.04	98.16	97.25	98.48	97.74	98.73	97.87	97.72	98.62	98.26	98.70	98.94		
LOI ^c	1.40	1.70	1.30	1.20	1.20	1.70	1.80	2.00	1.20	2.20	1.80	1.20	1.50	1.70	1.70		
Sp.Gr. ^d	2.79	2.77	2.76	2.73	2.71	2.74	2.74	2.71	2.76	2.81	2.70	2.73	2.70	2.71	2.73		
Trace Elements ^e																	
Au	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	3	<2	410	341
Ba	170	190	350	480	680	150	490	870	50	60	130	60	590	700	800		
Be	2	2	2	2	2	1	2	2	2	2	1	2	2	2	2		
Co	18	25	31	24	21	23	21	22	10	23	10	8	9	11	18	17.1	5.7
Cr	135	126	126	130	133	124	121	134	111	109	72	77	69	69	70	112.2	22.6
Cu	9	11	147	35	73	16	52	49	6	5	15	11	20	21	42	35.2	58.8
Li	10	12	12	10	11	16	11	15	7	13	10	6	12	12	10	10.3	3.1
Mo	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10		
Nb	15	18	7	7	8	7	1	12	10	10	<1	9	4	3	2	8.8	4.0
Ni	54	70	68	50	56	42	50	54	39	68	36	60	47	43	55	50.8	8.8
Pb	<10	<10	<10	<10	<10	<10	<10	<10	61	<10	75	<10	<10	11	<10		
Pd	<1	<1	<1	1	1	1	1	1	1	1	<1	<1	<1	<1	<1		
Pt	2	2	2	2	3	2	1	1	1	2	1	2	<1	2	1		
Rb	10	20	30	70	100	30	80	130	<10	<10	10	<10	40	70	80	54	33
Sc	10	10	7	8	9	8	6	10	9	7	5	8	7	5	5	8.5	1.8
Sr	50	40	75	70	115	35	55	100	65	30	22	30	35	45	45	75	45
V	90	95	135	80	80	75	75	80	90	95	50	65	55	70	50	90	29
Y	16	17	13	12	13	11	10	15	13	12	7	14	12	12	13	12.8	2.2
Zn	34	42	31	24	28	27	98	41	24	35	26	20	29	25	37	32.6	16.6
Zr	160	150	150	145	150	145	115	150	155	140	115	120	120	120	115	143	16

Samples: *1-3: South Range
 *4-30: North Range
 *24-30: North Range, part of sampled section (lower to upper) in Capreol Township; see Figure 7.17, and Table 7.11 for remainder of sampled section

Notes:

^a uncorrected weight percent ^b total Fe as Fe₂O₃ ^c loss on ignition ^d specific gravity

^e Au, Pd, Pt as ppb; all others as ppm

^f Data normalized to be volatile free; $\bar{x}$ = mean, σ = standard deviation

^g Muir (current research); chemical analyses by Geoscience Laboratories, Ontario Geological Survey.

CHAPTER 7

TABLE 7.11: CHEMICAL ANALYSES OF BLACK MEMBER (WHOLE ROCK) SPECIMENS, ONAPING FORMATION.

SAMPLE REFERENCE NUMBER	1	2	3	4	5	6	7	8	9	10	11	$\bar{x}$	σ
Major Oxides and Volatiles ^a													
SiO ₂	60.00	59.50	59.90	61.20	60.30	62.40	60.60	61.10	61.10	58.70	59.60	62.39	1.32
TiO ₂	0.71	0.69	0.92	0.62	0.77	0.76	0.64	0.62	0.60	0.74	0.40	0.70	0.13
Al ₂ O ₃	11.80	11.70	12.10	11.20	11.70	11.80	11.40	11.60	11.80	11.90	8.78	11.80	0.77
Fe ₂ O ₃	10.20	10.80	8.76	9.68	9.56	8.63	9.66	8.95	9.15	11.20	1.32	9.99 ^c	0.89
FeO ^b											7.61		
MnO	0.20	0.21	0.20	0.25	0.20	0.20	0.24	0.24	0.27	0.18	0.60	0.26	0.13
MgO	4.70	4.78	4.84	4.19	5.07	4.31	4.65	4.42	4.40	5.36	3.72	4.73	0.43
CaO	3.69	3.64	3.45	3.38	3.50	4.17	4.91	4.56	5.69	2.53	5.85	4.27	1.12
Na ₂ O	3.12	3.26	3.47	3.18	4.07	2.48	2.46	3.20	1.63	2.75	0.90	2.85	0.90
K ₂ O	2.85	2.51	2.80	2.77	1.78	2.43	2.15	2.68	2.72	2.02	1.89	2.50	0.38
P ₂ O ₅	0.05	0.05	0.05	0.05	0.06	0.05	0.06	0.05	0.06	0.05	0.12	0.06	0.02
CO ₂	0.17	0.56	1.03	1.38	2.27	1.54	1.79	1.46	1.36	2.21	6.52		
S	0.67	0.60	0.19	0.42	0.76	0.31	0.55	0.57	0.46	0.62	0.49	0.53	0.17
H ₂ O +	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.24		
H ₂ O-	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.32		
Total	98.16	98.30	97.71	98.32	100.04	99.08	99.11	99.45	99.24	98.26	100.36		
LOI ^d	1.60	2.20	2.20	2.40	2.90	2.20	2.30	2.00	2.00	3.30	7.90		
Sp.Gr. ^e	2.80	2.79	2.77	2.74	2.77	2.78	2.80	2.79	2.80	2.75	2.70		
Trace Elements ^a													
Au	6	< 2	< 2	5	< 2	< 2	< 2	< 2	< 2	< 2	4		
Ba	720	780	760	680	510	640	530	680	720	630	660	665	85
Be	2	2	2	2	2	2	2	2	2	2	n.d.		
Co	23	25	15	16	24	23	20	20	19	22	17	20.4	3.4
Cr	122	123	127	126	110	126	111	114	117	118	88	116.8	11.1
Cu	66	63	24	52	109	44	44	43	58	66	32	54.6	22.2
Li	9	12	13	11	14	13	14	12	14	24	18	14.0	4.0
Mo	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	n.d.		
Nb	11	9	12	8	16	<1	10	9	11	17	n.d.	17.3	18.8
Ni	67	69	61	50	64	49	52	53	56	61	49	57.4	7.4
Pb	155	<10	<10	33	<10	<10	<10	<10	<10	<10	<10		
Pd	<1	1	1	1	1	1	1	1	1	<1	n.d.		
Pt	2	2	2	2	1	1	1	1	1	<1	n.d.		
Rb	70	70	80	70	50	80	70	90	90	60	70	73	13
Sc	8	7	9	9	9	5	8	9	10	9	n.d.	8.3	1.4
Sr	70	45	50	55	55	100	150	85	165	65	190	78	45
V	145	90	90	80	95	90	85	80	80	90	n.d.	97	23
Y	16	13	16	17	19	10	15	14	17	18	20	15.5	2.6
Zn	45	42	43	50	46	60	56	46	73	56	102	56.3	17.7
Zr	155	140	145	140	135	115	135	140	140	150	140	140	11

Samples: ^a1 to 9 North Range: part of sampled section (lower to upper) in Capreol Township; see Figure 7.17 and Table 7.10 for remainder of sampled section

^a10 North Range: lower part of Black Member

^a11 North Range: upper part of Black Member

Notes:

^a uncorrected weight percent

^b total Fe as Fe₂O₃ where blank

^c loss on ignition

^d specific gravity

^e Au, Pd, Pt as ppb; all others as ppm

^f Data normalized to be volatile free; $\bar{x}$ = mean, σ = standard deviation

^g total Fe as Fe₂O₃ for all samples

n.d. not determined

^hMuir (current research): chemical analyses by Geoscience Laboratories, Ontario Geological Survey

ⁱMuir (1983, Table 7): chemical analyses by Geoscience Laboratories, Ontario Geological Survey

TABLE 7.12: CHEMICAL ANALYSES OF FLUIDAL-TEXTURED GLASS FRAGMENTS (SET A), ONAPING FORMATION.

SAMPLE REFERENCE NUMBER	1	2	3	4	5	6	7	8	9	10
Major Oxides and Volatiles ^a										
SiO ₂	61.63	61.67	65.27	56.61	57.06	60.48	66.75	55.76	61.82	63.76
TiO ₂	0.58	0.30	0.39	0.74	0.56	0.77	0.43	0.31	0.69	0.36
Al ₂ O ₃	15.41	14.02	15.51	12.10	9.19	14.36	15.21	14.59	16.24	18.41
FeO ^b	4.92	4.55	6.05	9.81	9.10	6.02	5.38	7.82	3.35	1.73
MnO	0.21	0.24	0.16	0.27	0.54	0.23	0.15	0.27	0.11	0.06
MgO	3.70	3.42	3.07	8.11	8.64	3.62	3.17	5.94	2.59	1.32
CaO	3.84	6.14	0.66	5.66	8.19	2.44	2.52	6.10	2.88	1.34
Na ₂ O	7.98	6.24	5.20	5.04	5.43	3.93	7.28	7.05	9.92	11.63
K ₂ O	1.75	5.12	3.82	0.98	0.56	5.32	2.27	0.38	0.25	0.14
Total	100.02	101.70	100.13	99.32	99.27	97.17	103.16	98.22	97.85	98.75

TABLE 7.12: CONTINUED

SAMPLE REFERENCE NUMBER	11	12	13	14	15	16	17	18	19	$\bar{x}^c$	σ^c
Major Oxides and Volatiles ^a											
SiO ₂	60.97	61.34	69.67	52.78	55.92	56.29	63.71	61.88	68.10	61.29	4.32
TiO ₂	0.56	0.60	0.39	0.18	0.36	0.24	0.55	0.43	0.10	0.45	0.19
Al ₂ O ₃	16.07	15.63	12.45	3.41	6.75	15.64	2.88	11.70	20.29	13.17	4.61
FeO ^b	5.38	4.07	3.36	16.02	12.39	6.13	7.70	5.92	0.50	6.36	3.72
MnO	0.11	0.11	0.05	0.63	0.48	0.26	0.49	0.27	0.07	0.25	0.17
MgO	4.13	3.19	2.09	12.72	10.00	7.80	10.80	8.11	1.22	5.48	3.50
CaO	4.55	2.99	0.46	11.40	9.39	12.45	10.33	5.14	0.34	5.12	3.79
Na ₂ O	9.34	4.41	2.94	0.52	2.89	0.0	3.21	6.06	11.07	6.12	3.01
K ₂ O	0.23	7.52	5.94	0.38	0.69	1.13	0.28	1.45	1.21	2.08	2.31
Total	101.34	99.86	97.35	98.04	98.87	99.94	99.95	100.96	102.90		

Samples: 1 to 19: Peredery (1972a), Table 12. Data from electron microprobe.

Notes:

^a uncorrected weight percent

^b total Fe as FeO

^c Data normalized to 100%; $\bar{x}$ = mean, σ = standard deviation

TABLE 7.13: CHEMICAL ANALYSES OF FLUIDAL-TEXTURED FRAGMENTS, FLUIDAL-TEXTURED BODIES, AND SPHERULITIC DIKES (SET B); ONAPING FORMATION.

SAMPLE REFERENCE NUMBER	1	2	3	4	5	6	7	8	9	10
Major Oxides and Volatiles^a										
SiO ₂	64.40	59.70	60.70	61.00	65.90	65.20	59.90	61.50	69.40	62.40
TiO ₂	0.71	0.86	0.85	0.86	0.92	0.76	0.59	0.71	0.78	1.01
Al ₂ O ₃	12.90	13.40	13.70	13.00	11.00	12.60	14.00	15.80	12.50	13.50
Fe ₂ O ₃	6.17	9.25	7.53	7.74	5.83	5.13	0.91	1.02	4.48	4.84
FeO ^b							6.40	4.94		
MnO	0.12	0.12	0.13	0.15	0.23	0.13	0.13	0.14	0.06	0.09
MgO	4.90	4.88	4.32	4.39	4.28	3.37	4.27	4.03	3.10	5.12
CaO	3.14	2.79	3.72	3.56	4.51	3.76	3.96	3.65	1.94	4.06
Na ₂ O	5.62	3.23	5.29	2.88	4.28	4.68	4.27	5.10	4.53	6.88
K ₂ O	0.49	3.43	2.16	5.39	1.90	3.06	2.25	1.81	0.91	0.22
P ₂ O ₅	0.04	0.05	0.04	0.04	0.04	0.05	0.12	0.12	0.01	0.05
CO ₂	0.08	0.07	0.08	0.10	0.36	0.14	0.14	0.09	0.29	0.12
S	0.04	0.04	0.02	0.05	0.23	0.19	0.01	0.03	0.01	0.01
H ₂ O +	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	1.49	0.69	n.d.	n.d.
H ₂ O -	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.38	0.40	n.d.	n.d.
Total	98.61	97.82	98.54	99.16	99.28	99.07	98.82	100.03	98.01	98.30
LOI ^c	1.30	1.80	0.80	0.90	0.90	1.00	1.10	0.90	1.50	0.90
Sp.Gr. ^d	2.72	2.73	2.78	2.74	2.77	2.72	2.78	2.77	2.68	2.75
Trace Elements^e										
Au	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ba	170	620	670	1720	570	690	520	310	270	80
Be	2	2	2	2	3	2	n.d.	n.d.	2	2
Co	17	24	18	19	9	33	24	18	17	12
Cr	135	154	133	130	90	120	133	145	93	160
Cu	6	240	5	10	16	32	8	8	5	6
Li	9	16	5	5	< 3	< 3	11	7	16	4
Mo	< 10	< 10	< 10	< 10	< 10	< 10	n.d.	n.d.	< 10	< 10
Nb	7	11	13	11	5	9	n.d.	n.d.	< 1	12
Ni	63	64	61	54	37	45	59	56	43	50
Pb	192	295	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Pd	1	1	1	1	< 1	1	n.d.	n.d.	< 1	< 1
Pt	2	2	2	1	2	2	n.d.	n.d.	< 1	1
Rb	< 10	110	80	190	70	110	100	80	40	< 10
Sc	9	9	12	10	9	12	n.d.	n.d.	6	12
Sr	175	125	135	90	60	105	220	80	180	65
V	125	140	120	130	60	120	n.d.	n.d.	80	90
Y	12	12	16	15	14	15	20	20	6	14
Zn	28	34	24	28	42	32	42	35	21	19
Zr	155	165	175	165	140	155	180	180	150	170

TABLE 7.13: CONTINUED

SAMPLE REFERENCE NUMBER	11	12	13	14	15	16	17	18	19	20
Major Oxides and Volatiles ^a										
SiO ₂	75.10	61.80	62.30	65.10	62.40	61.00	65.20	60.30	59.90	56.70
TiO ₂	0.58	0.93	0.85	0.78	0.74	0.82	0.69	0.79	0.92	0.81
Al ₂ O ₃	9.87	12.60	13.30	12.30	11.40	16.40	12.10	14.20	14.00	15.90
Fe ₂ O ₃	4.12	8.12	6.95	7.89	9.25	7.02	7.60	7.50	7.36	1.39
FeO ^b										7.05
MnO	0.06	0.12	0.14	0.14	0.13	0.10	0.11	0.09	0.11	0.12
MgO	2.20	4.76	4.68	5.04	4.95	2.29	3.12	3.75	4.80	5.22
CaO	0.70	3.20	2.72	1.88	2.78	0.72	2.58	1.91	1.86	2.24
Na ₂ O	1.06	3.33	4.75	4.31	4.24	0.0	4.40	1.27	1.75	4.16
K ₂ O	4.54	3.10	2.11	0.29	0.85	9.02	2.37	7.27	5.26	2.25
P ₂ O ₅	0.0	0.04	0.05	0.04	0.04	0.07	0.03	0.06	0.05	0.15
CO ₂	0.2	0.11	0.11	0.09	0.10	0.09	0.24	0.11	0.10	0.18
S	0.02	0.03	0.03	0.11	0.02	0.25	0.68	0.05	0.26	0.0
H ₂ O +	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.32
H ₂ O-	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.40
Total	98.47	98.14	97.99	97.97	96.90	97.78	99.12	97.30	96.37	98.89
LOI ^c	1.60	1.80	1.90	2.30	2.10	2.10	1.70	1.90	2.30	2.30
Sp.Gr. ^d	2.63	2.74	2.73	2.75	2.73	2.68	2.74	2.70	2.72	2.74
Trace Elements ^e										
Au	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	6
Ba	1920	710	490	120	190	4260	720	2290	2820	1550
Be	1	2	2	2	2	1	1	1	2	n.d.
Co	7	20	16	21	21	13	23	26	21	33
Cr	63	134	135	117	96	202	129	145	154	168
Cu	36	7	6	12	6	15	90	62	32	10
Li	9	12	12	18	14	22	7	18	18	19
Mo	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	n.d.
Nb	< 1	11	12	7	7	20	4	6	13	n.d.
Ni	34	60	56	47	56	63	37	64	56	75
Pb	< 10	< 10	< 10	< 10	48	< 10	< 10	< 10	< 10	< 10
Pd	< 1	1	1	1	< 1	1	< 1	2	1	n.d.
Pt	1	2	2	2	2	1	1	2	1	n.d.
Rb	150	110	60	< 10	20	320	80	260	160	90
Sc	5	11	11	8	7	25	8	8	11	n.d.
Sr	90	115	155	120	45	450	60	350	235	140
V	40	75	80	75	125	140	70	125	80	n.d.
Y	5	16	14	10	12	22	10	10	14	30
Zn	29	30	37	36	32	60	25	54	42	48
Zr	120	145	160	140	135	140	150	170	170	190

Samples: 1, 2: fluidal-textured bodies within Gray Member near Melt Bodies

3, 4: fluidal-textured fragments within Black Member

5 to 15: fluidal-textured fragments within Gray Member

16, 17: either fluidal-textured fragments or deformed, siltstone fragments (within Gray and Black Member, respectively)

18 to 20: spherulitic dikes within Gray Member

Notes:

^a uncorrected weight percent

^b total Fe as Fe₂O₃ where blank

^c loss on ignition

^d specific gravity

^e Au, Pd, Pt as ppb; all others as ppm

n.d. not determined

All samples from North Range: whole rock analyses

Samples 1 to 6, 9 to 19: Muir (current research): chemical analyses by Geoscience Laboratories,

Ontario Geological Survey

Samples 7, 8, 20: Muir (1983), Table 7: chemical analyses by Geoscience Laboratories,

Ontario Geological Survey

CHAPTER 7

TABLE 7.14: CHEMICAL ANALYSES OF UPPERMOST GRANOPHYRES IN THE UPPER ZONE OF THE SUDBURY IGNEOUS COMPLEX.

SAMPLE REFERENCE NUMBER	1	2	3	4	5	6	7	8	9	10	11	12
Major Oxides and Volatiles ^a												
SiO ₂	69.95	69.93	65.11	65.19	64.48	61.78	61.52	65.46	64.90	63.75	69.95	70.19
TiO ₂	0.83	0.79	0.77	0.83	0.75	0.45	0.52	0.51	0.48	0.50	0.69	0.60
Al ₂ O ₃	12.67	12.67	14.22	13.64	13.93	13.99	14.75	14.84	14.81	14.78	12.82	12.82
Fe ₂ O ₃	1.77	1.77	1.70	2.54	2.03	1.60	1.73	1.23	1.52	1.39	0.93	1.13
FeO ^b	3.63	4.01	5.87	4.37	5.18	8.81	8.59	4.16	3.95	4.80	4.16	3.87
MnO	0.13	0.14	0.19	0.18	0.21	0.22	0.26	0.15	0.15	0.13	0.14	0.14
MgO	0.83	0.95	1.89	2.04	2.42	3.86	4.06	2.69	2.94	3.11	1.34	1.13
CaO	2.12	2.01	2.13	2.97	2.29	0.67	0.57	2.34	2.65	2.22	1.18	1.49
Na ₂ O	3.31	3.60	3.00	3.37	4.41	2.11	3.30	3.37	2.91	4.40	3.15	2.83
K ₂ O	3.40	3.29	2.45	3.14	3.51	2.40	1.61	3.69	3.77	3.66	4.06	4.28
P ₂ O ₅	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO ₂	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	98.84	98.86	97.34	98.27	99.21	95.89	96.91	98.64	98.08	98.74	98.42	98.48
LOI ^c	0.90	0.90	1.90	0.90	1.50	2.80	2.80	1.70	1.70	1.90	1.30	1.20
Sp.Gr. ^d	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

TABLE 7.14: CONTINUED

SAMPLE REFERENCE NUMBER	13	14	15	16	17	18	19	20	21	$\bar{x}$	σ
Major Oxides and Volatiles ^a											
SiO ₂	71.40	70.00	57.50	70.50	67.20	69.40	73.50	64.10	68.70	68.40	3.87
TiO ₂	0.65	0.87	0.94	0.93	0.87	0.81	0.69	0.75	0.80	0.73	0.16
Al ₂ O ₃	11.90	12.60	17.80	12.90	13.20	12.80	12.20	13.90	13.40	13.92	1.40
Fe ₂ O ₃	5.21	5.38	7.00	4.33	6.92	5.60	3.60	7.27	4.41	6.57 ^b	2.12
FeO ^c											
MnO	0.09	0.09	0.12	0.06	0.14	0.09	0.07	0.17	0.06	0.14	0.06
MgO	2.73	1.29	2.94	1.05	1.86	1.67	1.73	4.89	3.21	2.34	1.20
CaO	1.32	1.60	3.91	2.32	2.21	2.68	0.98	1.10	0.78	1.93	0.87
Na ₂ O	2.92	1.79	4.94	4.82	2.87	3.01	3.32	2.52	4.07	3.50	0.88
K ₂ O	2.14	4.28	1.49	1.80	2.14	2.09	1.28	1.80	1.07	2.77	1.06
P ₂ O ₅	0.0	0.07	0.25	0.07	0.07	0.08	0.01	0.05	0.03	0.08	0.08
CO ₂	0.08	0.11	0.11	0.14	0.18	0.12	0.14	0.12	0.12		
S	0.03	0.06	0.02	0.01	0.01	0.01	0.03	0.01	0.01	0.02	0.02
Total	98.47	98.14	97.02	98.93	97.67	98.36	97.55	96.68	96.66		
LOI ^d	1.70	1.50	1.90	0.80	1.60	0.90	1.40	2.90	1.90		
Sp.Gr. ^e	2.69	2.69	2.75	2.69	2.75	2.78	2.69	2.70	2.66		
Trace Elements ^a											
Au	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	3		
Ba	500	1300	960	540	740	740	480	650	160	675	323
Be	2	2	3	2	2	2	2	2	1		
Co	14	10	14	9	12	9	6	21	14	12.1	4.3
Cr	92	< 5	27	< 5	6	< 5	33	135	120	44.2	56.4
Cu	26	18	37	5	9	6	10	38	7	17.3	13.2
Li	21	10	16	6	12	9	8	20	10	12.4	5.3
Mo	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10		
Nb	3	11	15	1	4	< 1	< 1	6	< 1	4.1	5.7
Ni	33	< 5	16	< 5	< 5	< 5	< 5	58	40		
Pb	110	< 10	< 10	< 10	< 10	< 10	14	48	< 10		
Pd	< 1	< 1	< 1	< 1	< 1	< 1	< 1	1	< 1		
Pt	1	1	< 1	< 1	< 1	< 1	< 1	2	< 1		
Rb	50	120	60	60	70	50	30	40	20	56	29
Sc	7	10	10	8	7	6	2	8	5	7.0	2.5
Sr	180	185	520	95	200	165	100	75	60	176	139
V	85	105	120	105	105	105	70	130	75	100	20
Y	8	20	14	9	9	9	3	7	5	9.3	5.0
Zn	44	42	51	24	65	45	42	235	32	64.4	65.0
Zr	150	210	200	195	150	175	150	160	165	173	24

Samples: * 1, 2: granophyre

* 3 to 5: plagioclase-rich granophyre

* 6 to 10: lenses in Basal Member

* 11, 12: "12" intrudes "11"

* 13 to 16: North Range; 16 is hybrid granophyre (associated with Basal Member)

* 17 to 21: South Range

Notes:

* uncorrected weight percent

* total Fe as Fe₂O₃ where blank

* loss on ignition

* specific gravity

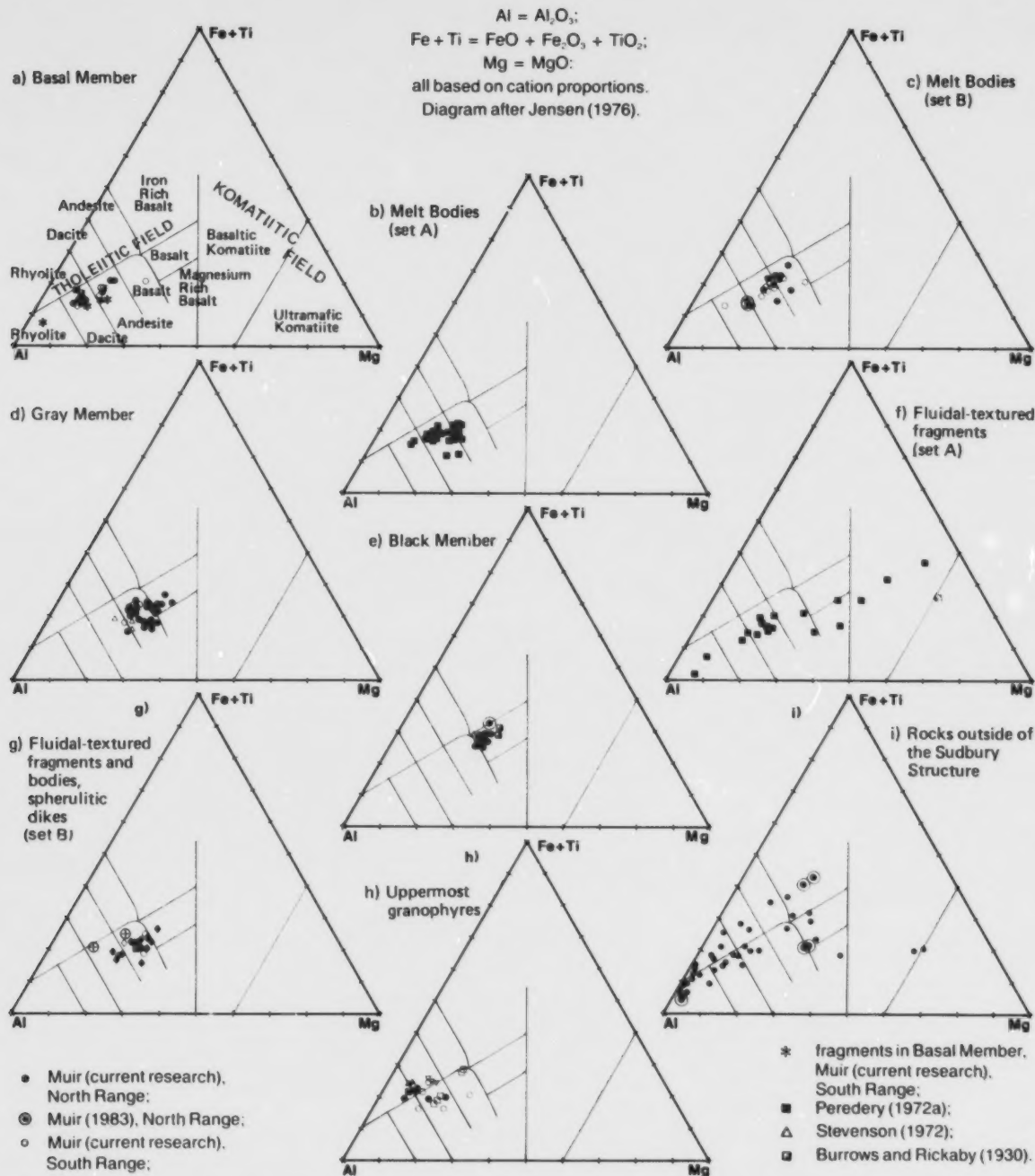
* Au, Pd, Pt as ppb; all others as ppm

* Data normalized to be volatile free; $\bar{x}$ = mean, σ = standard deviation* total Fe as Fe₂O₃ for all samples

n.d. not determined

* Peredery (1972a), Table 3

* Muir (current research); chemical analyses by Geoscience Laboratories, Ontario Geological Survey



- a) Basal Member matrices (data given in Table 7.7);
 b) Melt Body samples (set A) (data given in Table 7.8);
 c) Melt Body samples (set B) (data given in Table 7.9);
 d) Gray Member breccias (whole rock) (data given in Table 7.10);
 e) Black Member breccias (whole rock) (data given in Table 7.11);
 f) fluidal-textured glass fragments (set A) (data given in Table 7.12);
 g) fluidal-textured fragments, fluidal-textured bodies, and spherulitic dikes (set B) (data given in Table 7.13);
 h) granophyres of the uppermost part of the Upper Zone, Sudbury Igneous Complex (data given in Table 7.14);
 i) rocks outside of the Sudbury Structure (North and South Ranges).
 References for data given in text. These rocks include all major rock types (igneous, sedimentary, and metamorphic) and are plotted for comparison only.

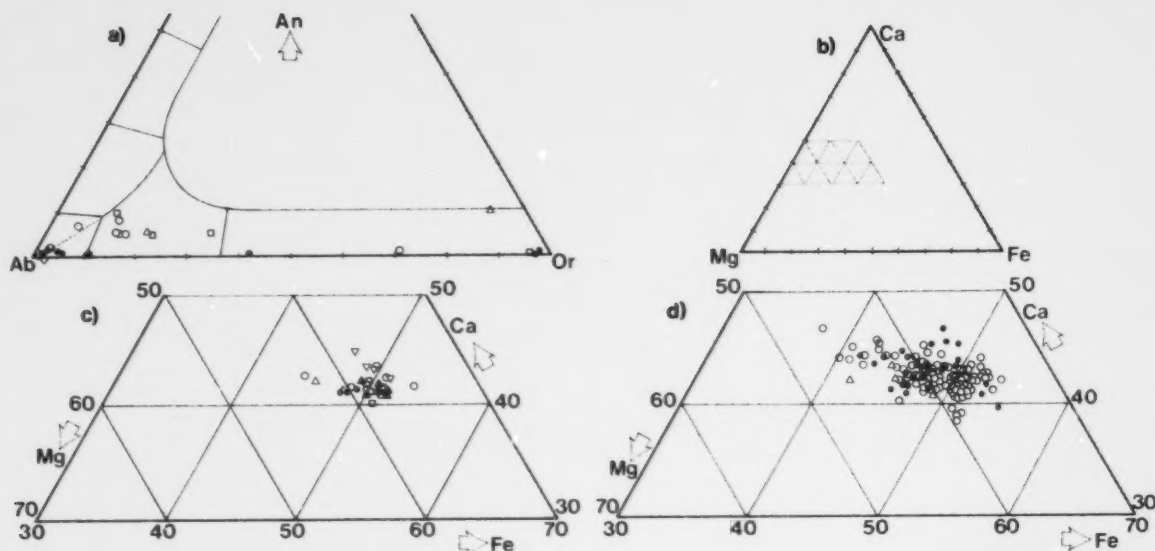
Figure 'f': 8 samples have olivine and nepheline, and 3 other samples have olivine, as part of their normative components.
 Figure 'g': ◊ spherulitic dikes; ○ fluidal bodies; ● fluidal fragments; ⊕ miscellaneous. (Data from Muir (1983; current research); see Table 7.13, this chapter).

Figure 'h': ▲ granophyre; ▽ plagioclase-rich granophyre; ◊ lenses in Basal Member; ■ miscellaneous; data from Peredery (1972a). Other symbols as per Muir (see above). See Table 7.14, this chapter.

Figure 'i': ● data from published literature (see text for references).

Rock Classification lines and terminology are for reference only.

Figure 7.14. Al - Fe + Ti - Mg Plot



a) Feldspar compositions for Basal Member and Melt Bodies: based on microprobe analyses for CaO, Na₂O, K₂O with SiO₂ and Al₂O₃ calculated as stoichiometric values; results recalculated for end-member feldspar molecules.
 ○ Basal Member matrix feldspars; △ Basal Member feldspathic clots; ◐ Basal Member igneous-textured patches; ● Melt Body matrix feldspars; ■ Melt Body feldspathic annealed inclusions; ◇ protobreccia feldspars.

b) Reference diagram for 'c)' and 'd)'.

c) Clinopyroxene compositions for Basal Member: derived from partial and complete microprobe analyses of specimens from

Dowling Township. Different symbols represent specific hand specimens.

○ pyroxene clusters; ▲ ◐ ◑ pyroxene grains and clusters; ▽ pyroxene in igneous-textured patches.

d) Clinopyroxene compositions for Melt Bodies: derived from partial and complete microprobe analyses of specimens from Dowling Township.

○ clinopyroxene in crystalline part (X); △ pyroxene rim on quartz inclusions in (X).

* clinopyroxene in brecciated variety of chilled part (Y);

▲ pyroxene rim on quartz inclusions in (Y).

Figure 7.15. Compositions of minerals from the matrices of the Basal Member and Melt Bodies (after Peredery 1972a).

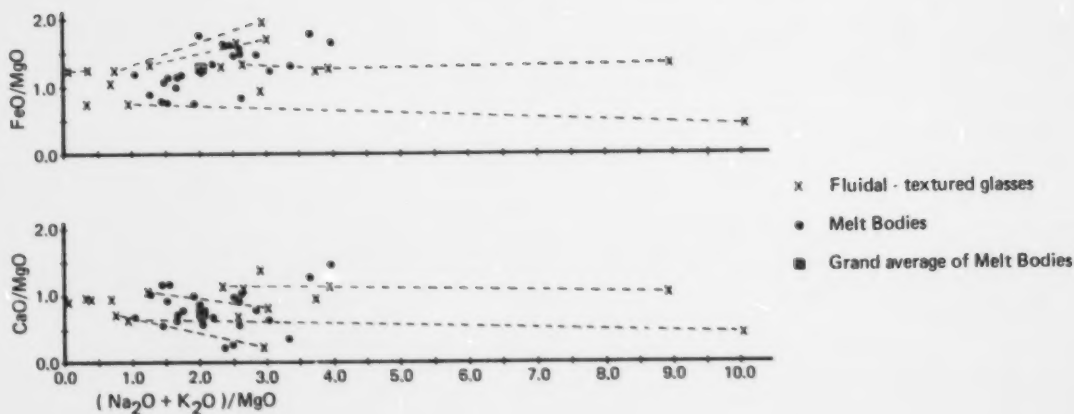


Figure 7.16. Plots of FeO/MgO and CaO/MgO versus (Na₂O + K₂O)/MgO for Melt Bodies and fluidal-textured glasses.

Various analyses of the same sample are joined by dashed lines. Data from Peredery (1972a); see Table 7.8, this chapter.

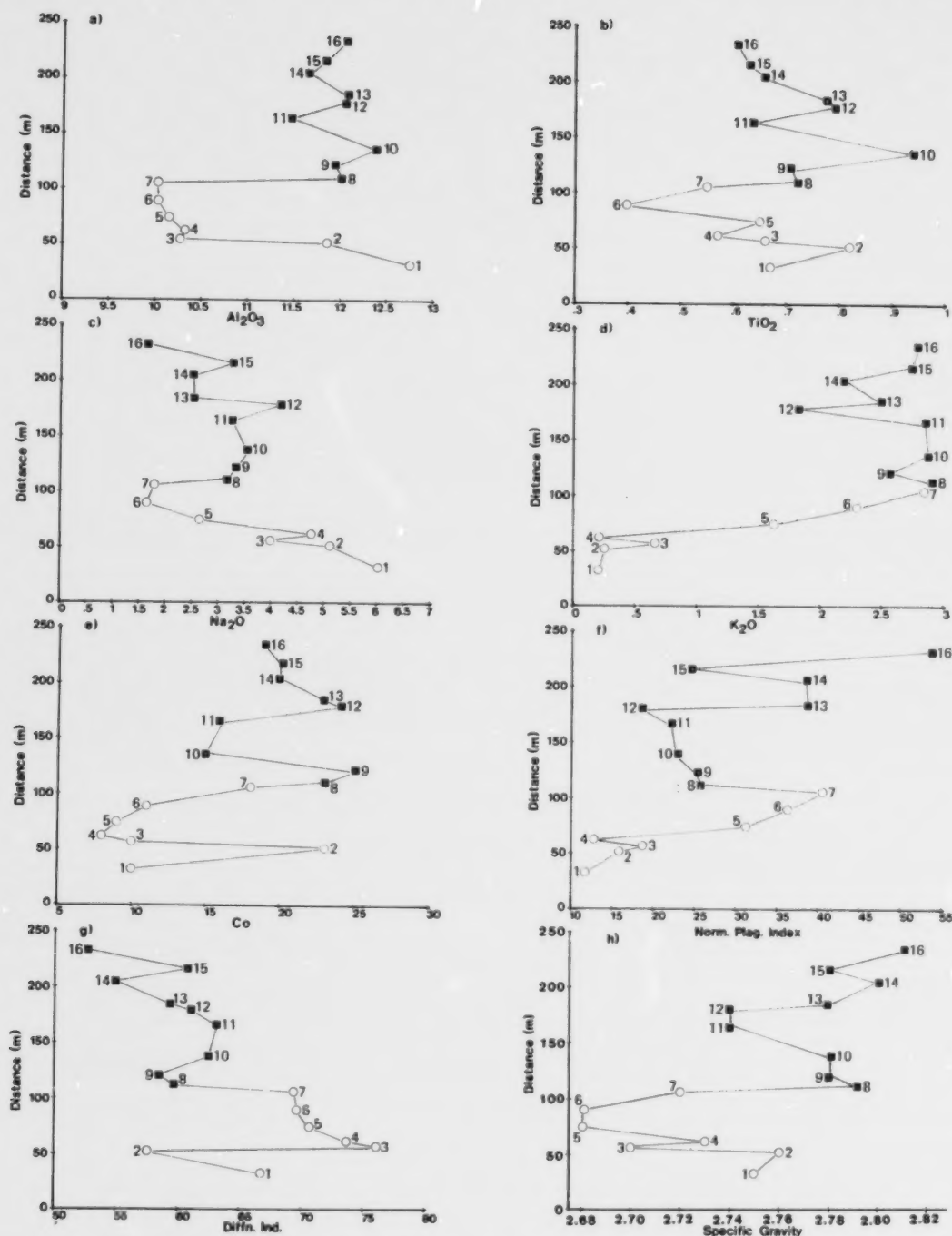


Figure 7.17. Variation of selected elements and functions in a section across part of the Onaping Formation, Capreol Township (area is within Figure 7.7). All vertical axes show the horizontal distance from the approximate contact between the Gray Member and Basal Member. Horizontal axes are as follows: a) Al_2O_3 (weight percent); b) TiO_2 (weight percent); c) Na_2O (weight percent); d) K_2O (weight percent); e) Co (ppm); f) normative plagioclase index (molecular) (after Thornton and Tuttle 1960); g) differentiation index (molecular) (after Irvine and Baragar 1971); h) specific gravity. Observed contacts lie between samples 2 and 3, 7 and 8, and 11 and 12. Sample 15 is from a mappable unit between samples 14 and 16, although contacts were not observed. There may be a contact between samples 1 and 2, as is suggested by some differences in lithologic characteristics of the matrices.

○ Gray Member (Muir, current research): numbers 1 to 7 correspond to sample reference numbers 24 to 30 in Table 7.10;

■ Black Member (Muir, current research): numbers 8 to 16 correspond to sample reference numbers 1 to 9 in Table 7.11.

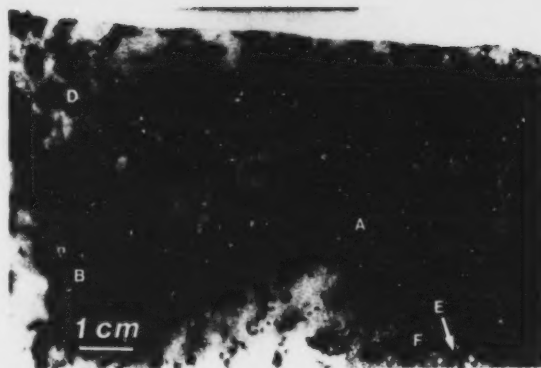


Photo 7.1. *Basal Member*: fragment-supported variety with fragments of various rock types. Norman Township.

Note: A) matrix; poor in potassic feldspar. B) matrix; rich in potassic feldspar with crudely developed micrographic intergrowth. C) medium-grained leucocratic granitoid rock. D) coarse-grained leucocratic granitoid rock. E) partly disintegrated feldspathic fragments in matrix. F) quartz fragments.

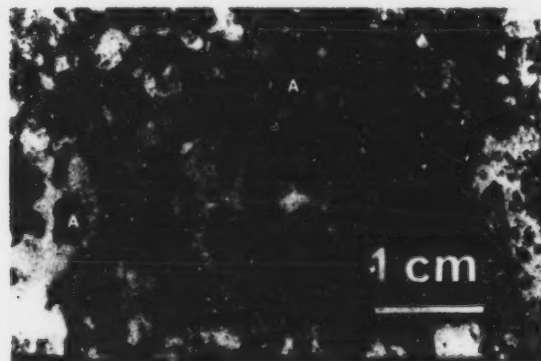


Photo 7.2. *Basal Member*: partly disintegrated fragments with 'Swiss cheese' texture. Norman Township.

Note: A) igneous-textured matrix which also fills holes in feldspathic material. B) feldspathic material of cryptocrystalline plagioclase and minor potassic feldspar.

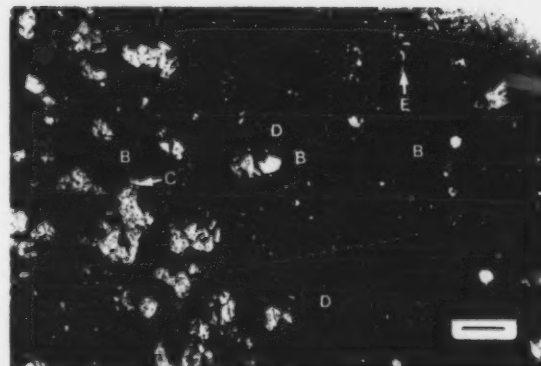


Photo 7.3. *Basal Member*: granitic fragment (left half) and matrix with partly disintegrated fragments (right half). Norman Township.

Note: A) quartz. B) cryptocrystalline plagioclase. C) intergrowth of quartz and potassic feldspar. D) very fine grained matrix with irregularly shaped quartz needles (lightest grey) in a crude intergrowth with plagioclase (moderately saussuritized), and

chlorite (commonly coarser than quartz or feldspar). E) clot or patch of fine-grained plagioclase laths, chlorite, actinolite, quartz, opaque needles, and some crudely developed micrographic intergrowth. Bar represents 2 mm. Plane light.

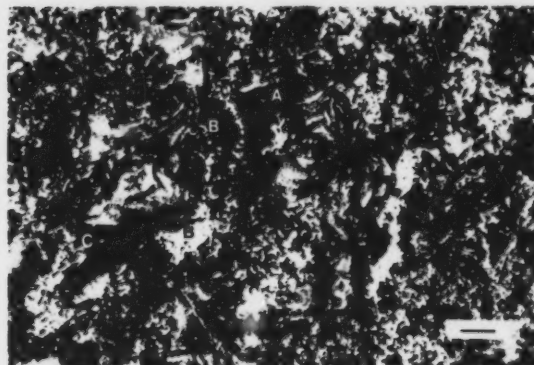


Photo 7.4. Photomicrograph of part of a 15 cm diameter fragment of leucocratic quartz monzonite within Basal Member. Norman Township.

Note: A) swirling patterns in microcrystalline plagioclase. B) mosaic-textured quartz in patches at various degrees of extinction. C) crudely developed micrographic intergrowth of quartz and potassic feldspar. Bar represents 1 mm. Crossed nicols.

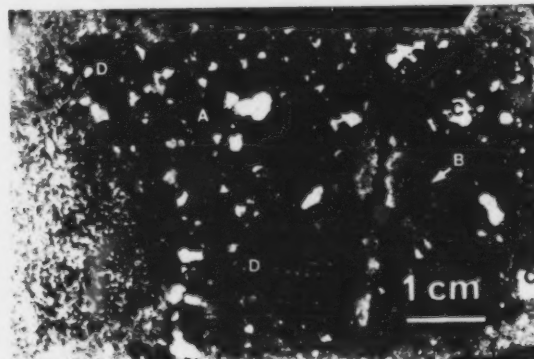


Photo 7.5. *Basal Member*: matrix-supported variety. Cascaden Township.

Note: A) very fine grained matrix with moderate amount of potassic feldspar. B) fine- to medium-grained igneous-textured patch with plagioclase, amphibole needles, and micrographic intergrowth of quartz and potassic feldspar. C) small fragments of cryptocrystalline plagioclase with embayed outlines. D) quartz fragments with embayed outlines. E) arkose fragment with 45% potassic feldspar, 40% quartz, 15% plagioclase.

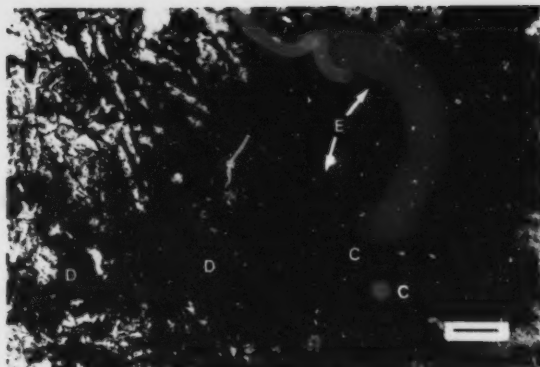


Photo 7.6. *Basal Member*: matrix with heterogeneous texture. Dowling Township.

Note: A) intergrowth of quartz (as crudely developed needles) and potassic feldspar. B) anhedral angular quartz crystals. C) plagioclase. D) chlorite after brown to green hornblende. E) needles of ilmenite. Bar represents 0.2 mm. Plane light.



Photo 7.7. *Basal Member*: Type 1 breccia with angular to sub-rounded fragments of metamorphosed white quartz arenite. Fragments do not show any internal deformation. Hammer is 0.4 m long. Garson Township.

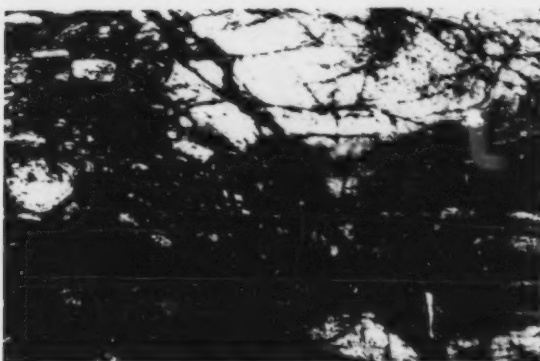


Photo 7.8. *Basal Member*: Type 2 breccia (on left) containing large block with weakly deformed bedding (on right). Virtually all fragments are metamorphosed, white, quartz arenite. Hammer head is 13 cm long. Garson Township.

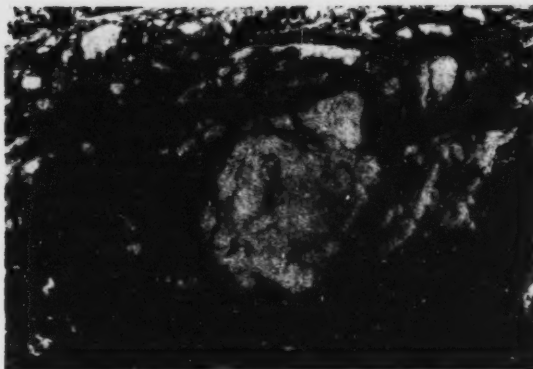


Photo 7.9. *Melt Body*: crystalline part with large and small fragments of white arkose and quartz arenite. Hammer is 0.4 m long. Capreol Township.

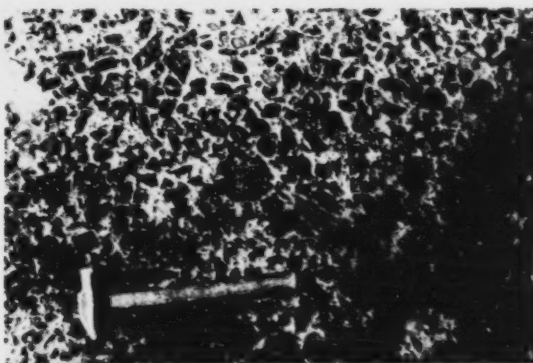


Photo 7.10. *Melt Body*: crystalline part with well-sorted (by size) angular to subrounded fragments of several varieties of arkose and quartz arenite. Hammer is 0.4 m long. Capreol Township.

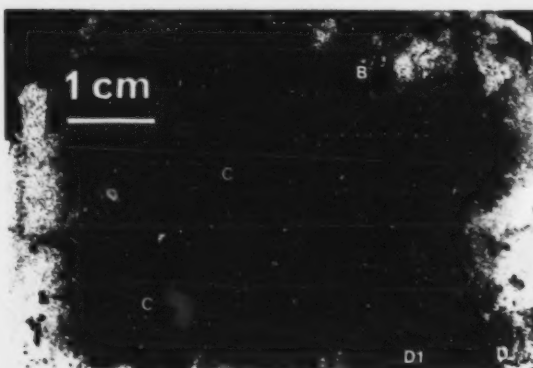


Photo 7.11. *Melt Body*: crystalline part. Capreol Township.

Note: A) matrix; fine grained with some medium-grained actinolite needles up to 4 mm long. B) arkose fragments with 50% potassic feldspar. C) quartz arenite fragments. D) fragment with interconnected and embayed feldspar and quartz, and a margin of individual rounded quartz crystals in a potassic feldspar 'matrix' (D1). E) microbreccia in quartz arenite.

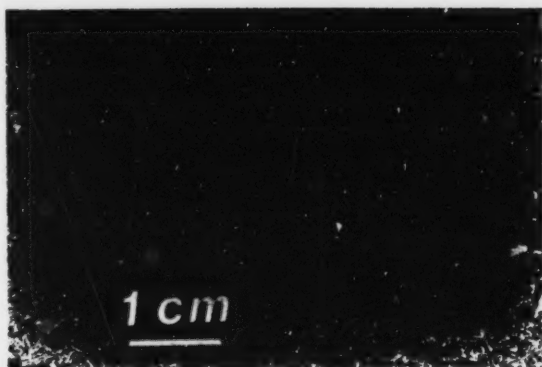


Photo 7.12. *Melt Body*: crystalline part with acicular actinolite crystals forming rosettes. Wisner Township.
- white needles are amphibole (specimen was etched in HF acid).
- matrix between needles consists of a crudely developed intergrowth of feldspar and quartz.

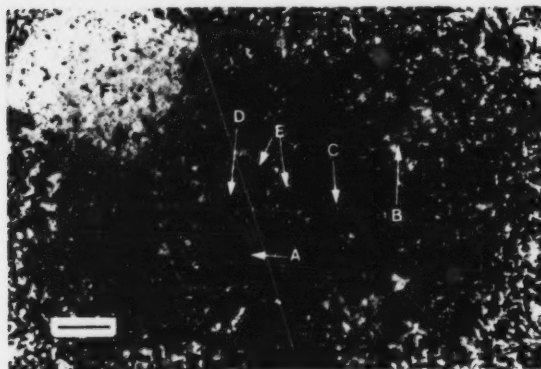


Photo 7.13. *Melt Body*: siliceous variety of crystalline part with heterogeneous texture. Capreol Township.
Note: A) patches of very fine grained micrographic intergrowth of quartz and potassic feldspar. B) fine-grained, angular, anhedral quartz, commonly associated with potassic feldspar. C) chlorite and stilpnomelane after amphibole laths and needles. D) needles of ilmenite. E) saussuritized plagioclase laths. F) quartz arenite fragment. Bar represents 1 mm. Plane light.

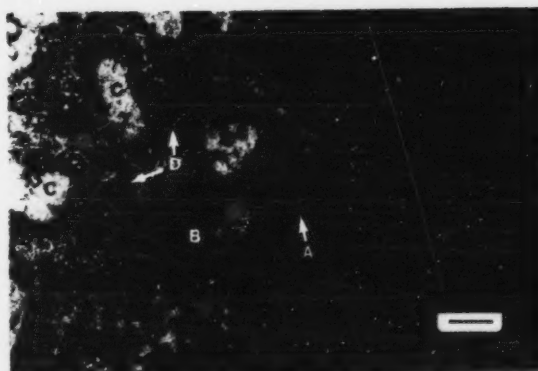


Photo 7.14. *Melt Body*: feldspathic variety of crystalline part with quartzose inclusion; same specimen as in Photo 7.11. Capreol Township.
Note: A) very fine grained to fine-grained actinolite needles with ragged ends. B) feldspathic matrix with antiperthitic laths and

extremely fine, local, micrographic intergrowth. C) partly recrystallized quartz 'xenocrysts' (weakly polycrystalline). D) borders around quartz xenocrysts consist of quartz needles (after tridymite?) and interstitial feldspar. Bar represents 0.2 mm. Plane light.

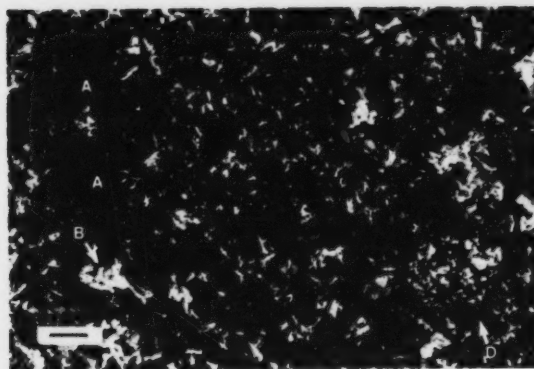


Photo 7.15. *Melt Body*: granophyric variety of crystalline part with fragment of cryptocrystalline plagioclase. Wisner Township. Matrix consists of fine- to very fine grained anhedral clinopyroxene (with actinolite and chlorite), and twinned plagioclase laths set in a crudely to moderately well-developed, fine-grained, micrographic intergrowth of potassic feldspar and quartz. Opaque minerals occur as needles and anhedral crystals.

Note: A) cryptocrystalline plagioclase fragment. B) relatively coarse micrographic intergrowth. C) round fragment (2.6 mm diameter, lower right corner) of fine-grained quartz arenite surrounded by; D) a rim of very fine grained clinopyroxene and actinolite. Bar represents 1 mm. Crossed nicols.



Photo 7.16. *Gray Member*: contact between Type 4 breccia with virtually no fragments >64 mm across (left, with 0.4 m long hammer) and overlying Type 2 breccia (right, with chisel); 15 m below top of Gray Member. Capreol Township.

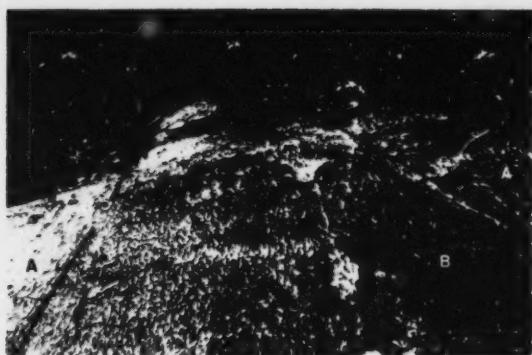


Photo 7.17. *Gray Member*: contact between Type 4 breccia ('A') and unit of well-sorted Type 3 breccia ('B'); about 150 m above base of *Gray Member*. Contacts marked by white lines. Garson Township. Hammer (0.4 m long) lies along left contact.

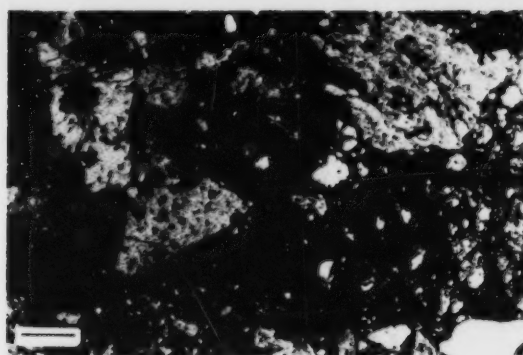


Photo 7.20. *Gray Member*: 2 m above sharp contact with another *Gray Member* unit (see Photo 7.21). Recrystallized matrix; numerous quartz and feldspar crystal fragments.

Note: A) simple felsic fragments with different textures. Bar represents 1 mm. Plane light.



Photo 7.18. *Gray Member*: relatively monolithic variety of Type 4 breccia. Note: A) brown, altered, felsic fragments with some vesicles (shown by 'V') and numerous crystals and crystal fragments (specific, unshocked angular quartz crystals shown by 'X'). B) the above material with banding. C) altered rectangular fragment consisting of very fine grained actinolite, biotite (?), and opaque minerals. D) siltstone. E) altered gabbro. F) chloritized fragment. Bar represents 2 mm. Plane light.

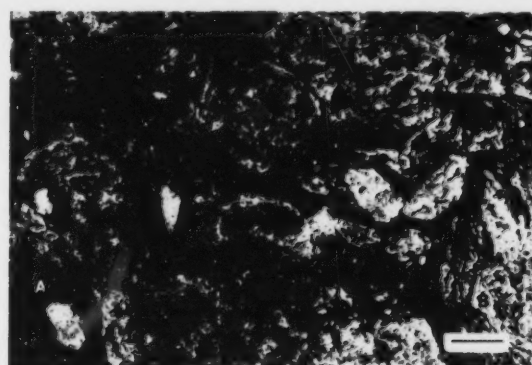


Photo 7.21. *Gray Member*: 2 m below sharp contact with another *Gray Member* unit (Photo 7.20). Finer part of matrix has many small angular felsic fragments. Most fragments are simple felsic glasses with titanite crystals (black dots).

Note: A) complex mafic fragment. B) complex felsic fragment. Bar represents 1 mm. Plane light.

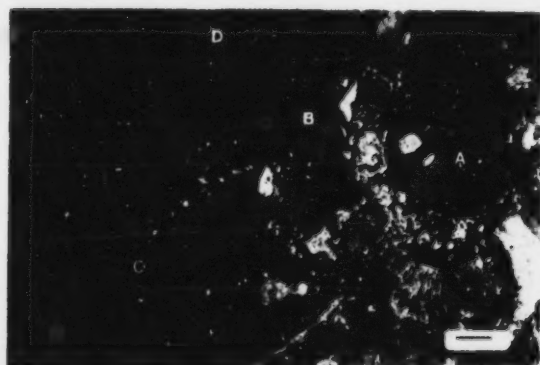


Photo 7.19. *Gray Member*: fragment-supported variety of Type 4 breccia.

Note: A) fluidal-textured fragment. B) complex felsic fragment. C) complex mafic fragment. D) simple felsic fragments. E) banded, simple felsic fragment. Bar represents 2 mm. Plane light.

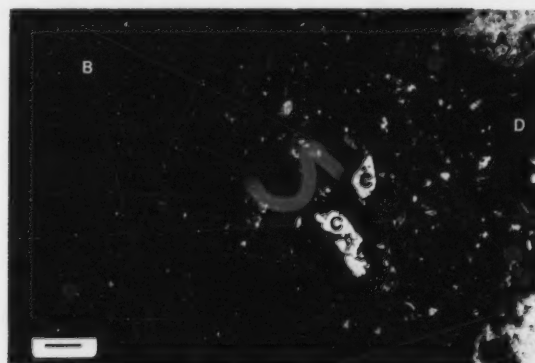


Photo 7.22. *Gray Member*: contact between 2 units; 55 m below Black Member. Left: Type 4 breccia with fine matrix, many small crystal fragments. Right: Type 2 breccia; matrix shows deformed fragments.

Note: A) simple felsic fragment. B) complex felsic fragment. C) cryptocrystalline felsic fragment. D) actinolitized fragment. Bar represents 2 mm. Plane light.

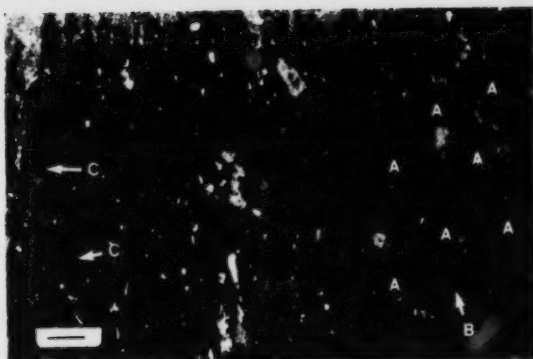


Photo 7.23. Fluidal-textured fragment: Gray Member.

Note: A) some highly flattened, plastically deformed fragments. B) flame-like terminations. C) flow-like banding. Bar represents 2 mm. Plane light.

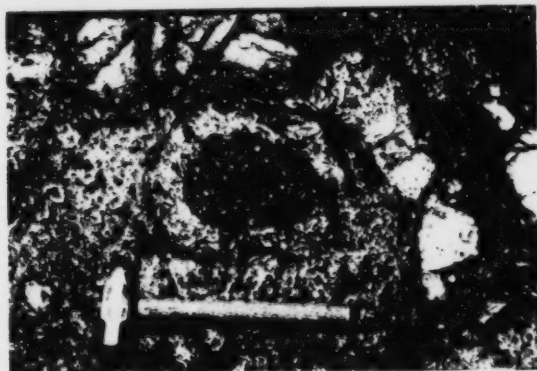


Photo 7.24. Composite fragment in Gray Member: fragment of fragment-supported Type 4 breccia, coated with fluidal-textured material (flow lines conformable to outline of fragment), within Type 2 breccia. Lumsden Township. Hammer is 0.4 m long.

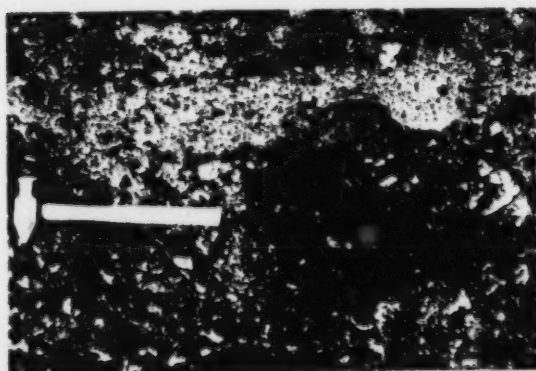


Photo 7.25. Contact between Type 4 breccia of Gray Member (lower half of photo) and Type 5 breccia of Black Member (upper half of the photo). The part of the Black Member shown is that which is rich in chloritized shard-like fragments with a green-grey matrix (i.e. little or no carbon). Capreol Township. Hammer is 0.4 m long.

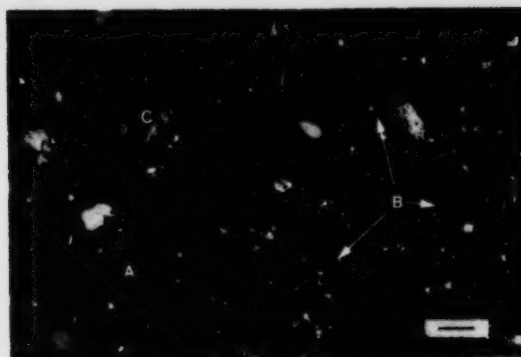


Photo 7.26. Black Member: 1 m above contact with Gray Member (see Photo 7.27). Matrix is grey-green; few carbon particles.

Note: A) black, fractured siltstone fragment. B) chloritized shard-like fragments. C) complex mafic (chloritized) fragment with discontinuous feldspathic rim. D) felsic complex glass. Bar represents 2 mm. Plane light.

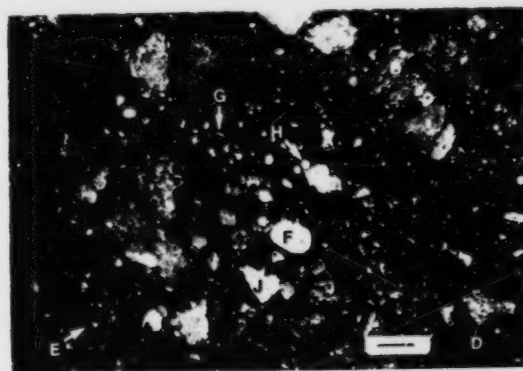


Photo 7.27 Gray Member: 2 m below contact with Black Member (see Photo 7.26). Matrix and many 'glass' fragments are rich in quartz crystal fragments. Angular quartz crystal fragments tend to be 'cloudy' (with minute inclusions); several fragments show remnant shock-metamorphic features. Well-rounded quartz crystal fragments tend to clear. Matrix and most glass fragments are significantly recrystallized especially compared to the overlying Black Member.

Note: A) complex felsic fragment (strongly recrystallized). B) complex felsic fragment (moderately recrystallized). C) simple felsic fragment (strongly recrystallized). D) complex mafic fragment. E) fragment of siltstone with several, relatively large, clean, quartz crystals and one equidimensional grain which is now chlorite. F) single, rounded, quartz crystal. G) polycrystalline quartz; main crystal has remnant decorated planar features. H) rounded, microcrystalline quartz. J) microcrystalline quartz with one well-embayed side. Bar represents 2 mm. Plane light.



Photo 7.28. *Black Member*: 2 m above contact with Gray Member (see Photo 7.29). Matrix is black; relatively rich in carbon particles.

Note: A) chloritized shard-like fragments with dense (dark 'clouds') of minute titanite crystals. B) chloritized shard-like fragments. C) cryptocrystalline felsic fragment. Bar represents 1 mm. Plane light.

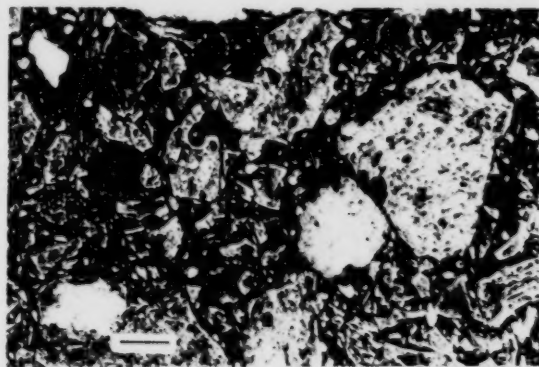


Photo 7.29. *Gray Member*: 2 m below contact with Black Member (see Photo 7.28). Matrix is black due to carbon particles. Most fragments are complex and simple felsic glasses.

Note: A) undeformed vesicles. B) highly deformed vesicles. Bar represents 1 mm. Plane light.

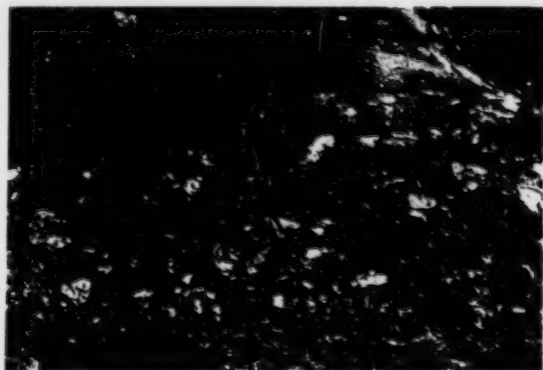


Photo 7.30. *Black Member*: contact between underlying Type 3 breccia (lower half of photo) and overlying Type 4 breccia (upper half); 60 m above Gray Member, Blezard Township. Hammer is 0.4 m long.



Photo 7.31. *Black Member*: several planar beds lying within a 10 cm thick 'unit' (upper and lower limits marked by arrows); 800 m above Gray Member. Attitude of beds is $135^{\circ}/25^{\circ}\text{SW}$. Regional attitude of the Onaping Formation is approximately $065^{\circ}/30^{\circ}\text{SE}$. Lumsden Township. Upper scale of card is in cm.

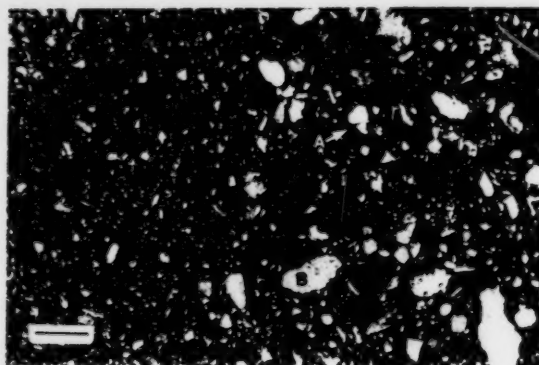


Photo 7.32. *Black Member*: contact between lens of coarse, Type 5 breccia and fine, Type 5 breccia. Left: fine-grained, Type 5 breccia; mostly fine-grained fragments of various types of glasses, quartz and feldspar crystal fragments, and sulphide fragments. Right: coarse-grained, Type 5 breccia with fragment types same as above.

Note: A) numerous, well-rounded quartz crystals. B) bedded silt-stone fragment. Bar represents 1 mm. Plane light.

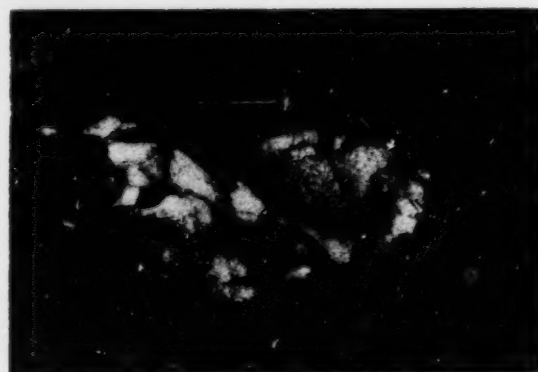


Photo 7.33. *Black Member*: composite, irregularly shaped fragment of Type 5 breccia in Type 4 breccia. Lumsden Township. Hammer is 0.4 m long.



Photo 7.34. Black Member: variety of fragments.

Note: A) simple mafic (actinolitized) fragment; weakly banded. B) simple felsic glass (vesicular). C) simple felsic glass (non-vesicular). D) fluidal-textured fragment. E) fragment of actinolite-chlorite with crystal fragments including rectangular quartz crystal. F) simple mafic (actinolitized) fragment (vesicular with plagioclase crystal fragment). G) complex felsic glass. Bar represents 0.5 mm. Plane light.

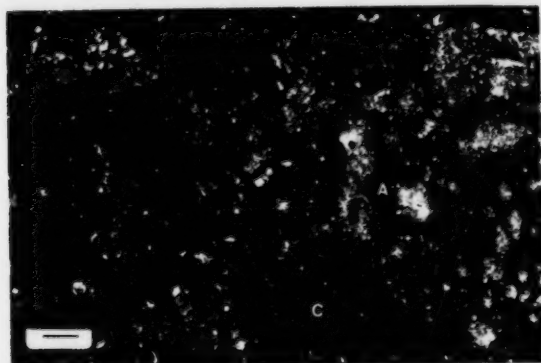


Photo 7.35. Spherulitic dike within Gray Member.

Note: A) spherules; extremely fine grained, equigranular. B) 'matrix' with extremely fine, unoriented, acicular (altered) minerals. C) 'matrix' with sets of parallel altered crystals. D) spherule-like growths; many have a quartz-actinolite amygdale-like feature at their centre. Bar represents 2 mm. Crossed nicols.

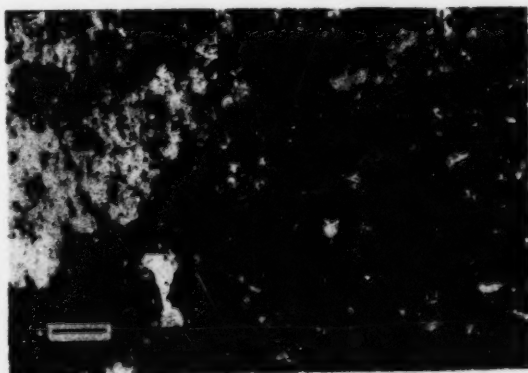


Photo 7.36. Thin section of part of 2 m diameter fragment of quartz monzonite within the Gray Member.

Note: Deformed, wavy, and swirling patterns in cryptocrystalline feldspar adjacent to large (2.8 cm long) recrystallized mega-

cryst of microcline (part of which is shown in the upper left corner). Microcline has numerous tiny inclusions giving it a 'cloudy' appearance. Bar represents 1 mm. Crossed nicols.

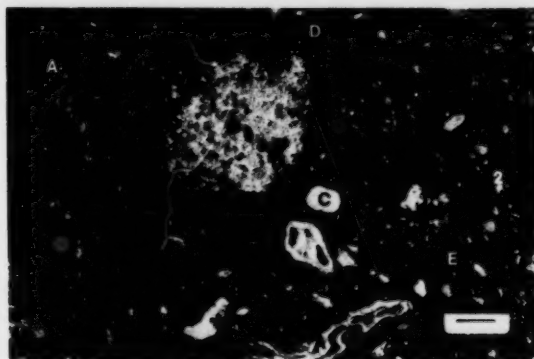


Photo 7.37. Black Member: variety of fragments.

Note: A) complex mafic (chloritized) fragments. B) unusual-textured complex felsic fragment. C) siltstone fragment. D) fluidal-textured fragment. E) microbreccia with complex texture; fragment appears to contain 2 distinct, but similar parts (labelled '1' and '2') and a chloritized glass fragment (not visible at this scale). Bar represents 2 mm. Plane light.

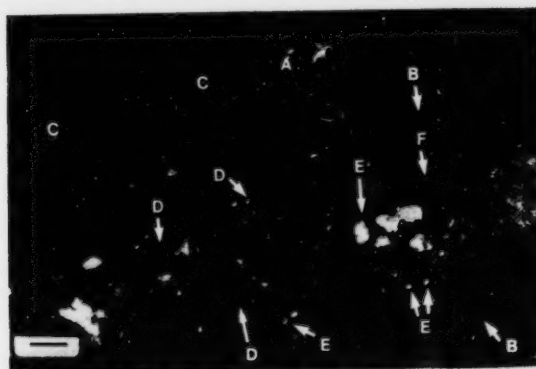


Photo 7.38. Microbreccia veinlet: within altered siltstone fragment in Black Member.

Note: A) bedding in siltstone fragment. B) limit of alteration (irregular) along walls of veinlet. C) microfractures. D) fragments of altered material with shard-like shapes; appear to have a composition different from the siltstone. E) oval and irregularly shaped fragments consisting of a core of a single quartz crystal with actinolite needles radiating inward from the outer edge. F) pieces of 'wall rock'. Bar represents 1 mm. Plane light.

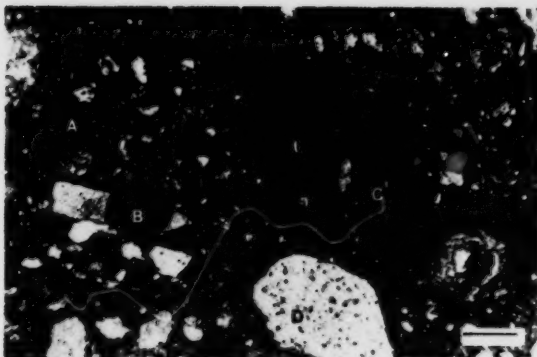


Photo 7.39. Sulphide fragments: *Gray Member*.

Note: A) pyrrhotite as a fragment. B) pyrrhotite within a fragment. C) fluidal-textured fragment with amygdule-like features. D) fine-grained quartzite. E) complex felsic fragment with carbonate. Bar represents 0.5 mm. Plane light.

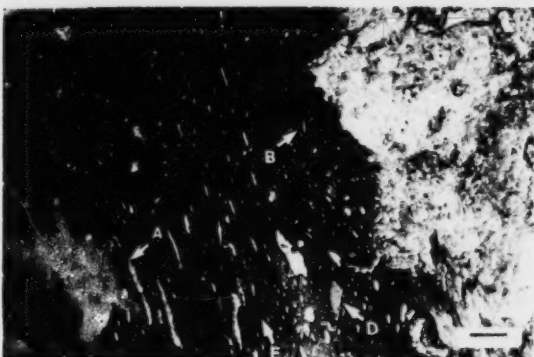


Photo 7.40. Fluidal-textured material: numerous vesicle-like features with weak, flow banding.

Note: A) highly flattened vesicle (now amygdule). B) oval vesicles (now amygdules). C) Gray Member breccia (host rock to fluidal-textured material). D) curved and angular chloritized fragment partly rimmed by feldspar. E) angular titanite crystal. Bar represents 2 mm. Plane light.

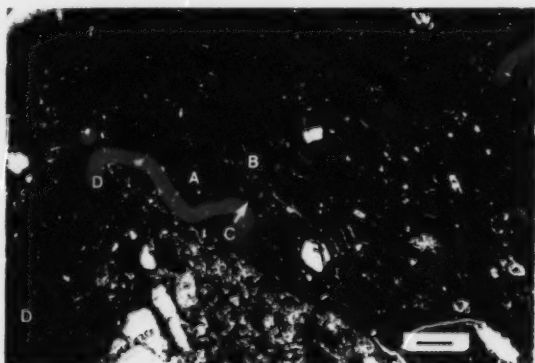


Photo 41. Fluidal-textured fragment with well-developed discontinuous banding: *Gray Member*.

Note: A) weakly contorted banding. B) highly contorted banding with discontinuous bands. C) sharp interface between 2 styles of banding. D) deformed glass fragments within Type 4 breccia; *Gray Member*. Bar represents 2 mm. Plane light.



Photo 7.42. Crystal fragment: *Gray Member*.

Note: A) well-rounded quartz crystal with irregular, embayed outline on one side and curved fracture through centre of the crystal. B) chloritized shard-like fragments. Bar represents 0.5 mm. Plane light.

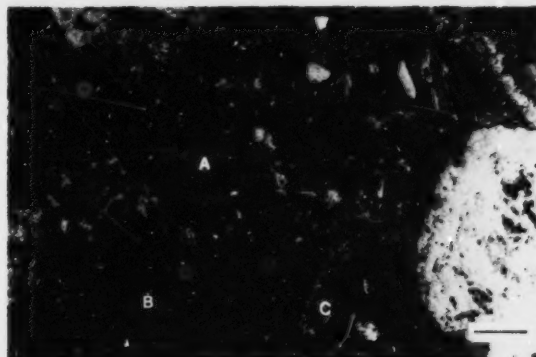


Photo 7.43 Crystal fragment: *Gray Member*.

Note: A) square 'crystal' of very fine grained acicular actinolite. B) well-banded, complex felsic glass. C) simple felsic glass with axiolitic rim. Bar represents 1 mm. Plane light.

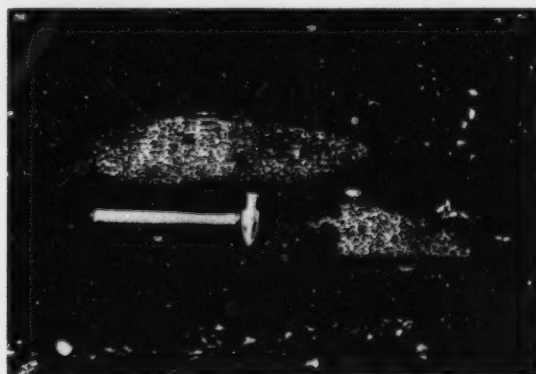


Photo 7.44. Composite fragments, *Gray Member*: 2 stretched fragments of well-sorted, coarser, Type 4 breccia in a well-sorted, finer, Type 4 breccia. Garson Township. Hammer is 0.4 m long.

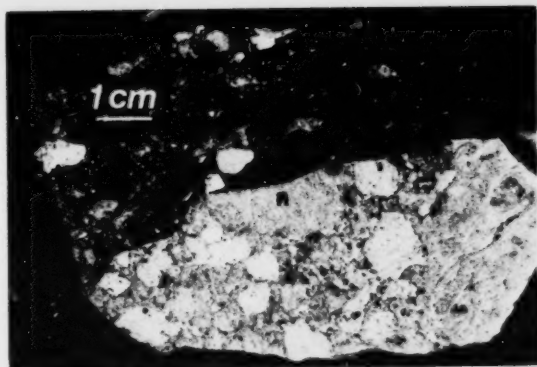


Photo 7.45. Composite fragment: *Black Member*. Morgan Township. Lower half of photo: part of a 20 cm diameter fragment of fragment-supported, grey, Type 3 breccia (truncated fragment of arkose shown as 'R'). Upper half of photo: Type 4 breccia of Black Member which hosts the above fragment of Type 3 breccia.

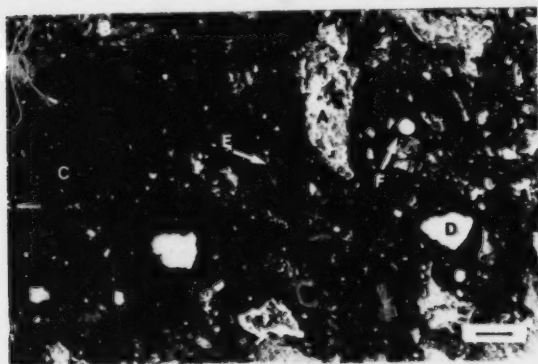


Photo 7.46. Composite fragment: *Black Member*.

Fragment of Type 5 breccia (1.5 cm diameter, bottom centre of photo) in Type 4 breccia. Type 5 breccia consists of rimmed, simple mafic fragments, some with shard-like shapes; composed of green-brown actinolite and actinolite-chlorite. Type 4 breccia consists of a wide variety of fragments plus many shard-like chlorite fragments.

Note: A) complex felsic (feldspathic) fragment. B) complex mafic (chloritized) fragment. C) fluidal-textured fragment. D) quartzite fragment. E) miscellaneous fragment; feldspar laths. F) well-rounded, very fine grained siliceous fragment. Bar represents 2 mm. Plane light.

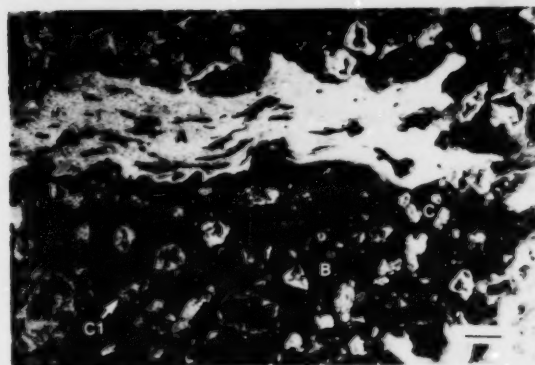


Photo 7.47. Composite felsic fragment: *Gray Member*.

Note: A) deformed, banded, simple felsic glass with cuspidal outline and flame-like termination; contains 0.3 mm diameter hexagonal crystal which is now chlorite (not visible in photo). B) cryptocrystalline felsic matrix. C) crystals (now very fine grained quartz); some have subhedral and embayed outlines (C1). Bar represents 1 mm. Plane light.

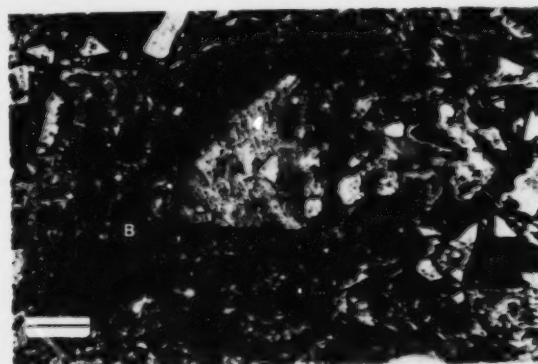


Photo 7.48. Composite fragment: *Gray Member* (with carbon particles).

Note: A) banded, subrounded, complex felsic glass fragment with quartz crystal fragments; within B) complex mafic glass fragment with broken vesicles (right end of fragment) and discontinuous rim of feldspar (upper left part of fragment). Bar represents 0.5 mm. Plane light.

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DISCUSSION OF THE ONAPING FORMATION

T.L. Muir

Listed below are points the author considers to be significant to a discussion about the Basal Member and the Melt Bodies.

1. Much of the Basal Member of the South Range is a "quartzite breccia" (Photos 7.10 to 7.12), as was interpreted by Stevenson (1961), and the Basal Member of the North Range consists mostly of granitoid fragments (Photos 7.1 and 7.3), locally with considerable amounts of arenite fragments.

However, locally the Basal Member has what may be rhyolitic fragments and anhedral feldspar phenocrysts. In these instances the Basal Member bears a striking resemblance to examples of rhyolite tuff-breccia such as that from Chabanel Township, 10 km north-northeast of Wawa, Ontario.

2. Most of the Basal Member of the South Range and a significant proportion of the Basal Member of the North Range have corresponding (that is, "underlying") brecciated Footwall rocks of significantly different composition (*see* Map 2491, back pocket). This strongly suggests that the Footwall breccias and the Basal Member breccias are neither directly related nor both autochthonous.
3. The cigar-shaped units of breccia within the Gray Member in northeastern Garson Township are interpreted to be lenses of Basal Member breccia faulted and/or tightly folded into their present position. This interpretation concurs with that of Stevenson (1961).
4. The unusual textures in fragments in the Basal Member of the North Range (Photos 7.2 and 7.4) are ascribed to partial fusion and/or shock metamorphism of Archean and Early Proterozoic granitoid and possibly arenaceous rocks, coupled with subsequent contact-metamorphic effects from the Sudbury Igneous Complex.
5. The chlorite pseudomorphs of subhedral to euhedral amphibole, and possibly pyroxene, locally present in the igneous-textured parts of the Basal Member matrix, may represent phenocrysts.
6. The Melt Bodies are interpreted to be hypabyssal intrusive rocks with possible lava flows, as indicated by their texture, structure, and position in the Onaping Formation. This conclusion largely concurs with Peredery (1972a).
7. The Melt Bodies analyzed have been shown to be fairly homogeneous on a hand specimen scale (Peredery 1972b). No analyses have been presented which show a range of composition of confirmed

Melt Bodies from rhyolite to andesite, either collectively or within single bodies, using AFM, Al-Fe+Ti-Mg (Figure 7.14), or QAP classification systems (compare with Peredery, Discussion of the Onaping Formation, this chapter).

8. Some of the "Melt Bodies" in the upper part of the Gray Member and in the Black Member may instead be large fragments or blocks of disrupted Melt Body units, based on their round shape in surface plan and lack of evidence of intrusion or extrusion.
9. Significant assimilation of fragments, derived from the Basal Member, by the Melt Body matrix is evident from the nearly ubiquitous inclusions visible in thin sections and outcrops (Photos 7.9, 7.10, 7.11, 7.13, and 7.15); and from the quartz-rich "aureoles" around many inclusions. Partial assimilation probably accounts in part for the range in textures (Photos 7.13 and 7.14) and compositions (Figure 7.14).
10. The author considers that the Melt Bodies are genetically related (directly or indirectly) to the plagioclase-rich granophyre of the Sudbury Igneous Complex, based on mineralogy, textures, and chemical composition. The latter was verified by using two-tailed Student's "t" test evaluations involving pooled and separate variance estimates at the 95% confidence level as outlined by Nie *et al.* (1975). A total of 85% of the elements (*see* Tables 7.8, 7.9, and 7.14) showed no statistically significant difference, about their means, between the Melt Bodies and granophyres.
11. The author considers the matrix of the Basal Member to consist, in part, of: 1) recrystallized, finely brecciated material, similar to the present constituent fragments, formed initially by one or more explosions; 2) igneous material derived from local, intimate intrusion of the plagioclase-rich granophyre and/or Melt Body magma; and 3) partly melted and metasomatized fragmented country rock material. Support for these interpretations comes from: the variation in grain size of the Basal Member matrix; the consistently higher proportion of mafic minerals in the matrix than in the fragments; the distribution of potassic feldspar and clinopyroxene (*see text*); albitization of plagioclase; and similar textures elsewhere associated with intrusions into feldspathic quartzite involving partial melting (Platten 1982).

Listed below are points considered to be significant with regard to the Gray Member and Black Member.

1. Some units of the Gray Member in the North Range dip steeply away from the present centre of the Sudbury Basin (Figure 7.7; section on Gray Member). There is little evidence of any tectonic deformation in this area. Locally, bedding in the Black Member

- strikes at right angles to the overall strike of the member. These facts suggest that the Onaping Formation has a more complex primary structure than has previously been considered, and this may negate a simple concept of basin or crater infilling.
2. The contact between the Gray and Black Members, and contacts between other units are irregular (Figure 7.7). These features indicate there was up to at least 50 m of relief at the time of deposition.
 3. The presence of shock-metamorphic features in some country rock and mineral fragments in the Gray and Black Members, coupled with the many breccia units and composite fragments which constitute the members, indicate that one or more events occurred with catastrophic effects from high-peak-pressure waves. No documentation has been published to demonstrate that only 1 shock-metamorphic event occurred.
 4. Microbreccia fragments (Photo 7.37) in the Onaping Formation bear a distinct resemblance to some varieties of Sudbury Breccia in the Footwall rocks (*see* Dressler, Chapter 6, this volume). This suggests that the microbreccia/Sudbury Breccia material was derived from the breaking up of rocks already containing this breccia in a consolidated form.
 5. Textures around some glass fragments and in the matrix, particularly in specific breccia units, likely represent axiolic mineral growth and vapour phase crystallization (Photo 7.41). Some breccia units which have undergone moderate devitrification and recrystallization of glass fragments are overlain by breccia units that have undergone considerable devitrification and recrystallization (*compare* Photos 7.21 and 7.22). Similar relationships can be found within and among cooling units in ash-flow tuffs (Smith 1960a, 1960b). The above relationships of differing degrees of devitrification and recrystallization is incompatible with contact metamorphism from the Sudbury Igneous Complex alone. This metamorphism has altered the lower part of the Gray Member, but decreases in intensity up-section.
 6. Intense to moderate welding is evident in medium-sized blocks within some units located well above the base of the Gray Member (Photos 7.23 and 7.41). Fiamme occur within some composite welded fragments (Photos 7.23 and 7.47). Several specimens of fluidal-textured fragments and bodies strongly suggest that some fluidal-textured material is composed of highly welded fragments which have undergone rheomorphic flowage and are now flow-banded. Schmincke (1974) and Lipman (1984) show examples, from other areas, of highly welded tuff, and rheomorphic flow in highly welded tuff, that are very similar to the examples cited in the Onaping Formation.
 7. Bombs and cored bombs are present in the Gray and Black Members (Photo 7.24). Some of these bombs have cores consisting of a breccia which is dissimilar to the breccia in which the cored bomb lies.
 8. Some fluidal-textured fragments with plastically deformed banding appear similar to mudstone from the Gowganda Formation of the Huronian Supergroup, and to lithified blocks of layered clay. These similarities should be further evaluated.
 9. Fragments consisting of sulphide minerals, which are mesoscopically similar to sulphide minerals found in the Sublayer of the Sudbury Igneous Complex, occur throughout the Onaping Formation (Photo 7.39), particularly in the Black Member. Whole rock analyses of specimens, containing sulphide mineral fragments, have slightly higher levels of Pt and Pd (Tables 7.7 and 7.13) compared to most rocks of the Sudbury Igneous Complex (excluding the Sublayer) and most country rocks analyzed (Tables 3 to 17 in Muir 1983). The fragments indicate that sulphide bodies had formed before and/or during the deposition of the Onaping Formation and were subsequently brecciated.
 10. Most crystal fragments in the Onaping Formation are likely xenocrysts. Some crystals within the matrix of many breccia units (Photos 7.42 and 7.43) or within simple or composite fragments (Photos 7.18, 7.47), however, appear similar to some whole and broken phenocrysts in various volcanic deposits (*see* Wilcox 1944; Ross and Smith 1961; Lipman 1975). The author interprets that these crystals are primary phenocrysts in the Onaping Formation. Many broken phenocrysts are difficult to distinguish from xenocrysts. Therefore, there may be more phenocrysts than presently recognized.
 11. Some fragments have igneous textures which cannot be readily associated with those of any of the igneous country rocks (*see* section on Miscellaneous Fragments). Although some fragments may be chilled porphyritic diabase, it is possible that others are igneous rocks formed in association with the Gray and Black Members.
 12. Composite fragments are present throughout the Gray and Black Members and occur at outcrop, hand specimen, and thin section scales (Figures 7.4, 7.11, 7.12, and 7.13; Photos 7.24, 7.33, 7.37, 7.38, 7.43 to 7.48). Some glass and lithic fragments have been broken and now define part of the outline of some composite fragments. This strongly suggests that these composite fragments were derived from lithified breccias. Complex composite fragments are common in volcanic rocks because of multiple events (*see* Ross and Smith 1961) and are found in lunar breccias, interpreted to be the result of *multiple* meteorite impacts (Lambert and Grieve 1984).

13. Various types of glass fragments, defined by morphology, texture, and composition are commonly found within individual hand specimens (Photos 7.26, 7.27, 7.34, and 7.43). Some volcanic deposits have composite and complex glassy fragments similar to those in the Onaping Formation, such as at Askja in Iceland, and the Dolly Varden Mountains in Nevada. These points can be explained by multiple eruptions of different magmas, including partly mixed magmas (*see* Ross and Smith 1961; Eichelberger 1975; Lipman 1975; Smith 1979; Sigurdsson and Sparks 1981). Other specimens from the Onaping Formation contain 1 predominant type of glass fragment (Photos 7.18, 7.21, 7.28, and 7.29). Textures such as shown in Photo 7.29 are similar to those of some volcanic deposits (*see* Heiken 1971).
14. There is no glass *per se* in the Onaping Formation. The present composition of individual glass fragments may bear only a partial resemblance to the original composition, and to what extent these were homogeneous cannot be firmly established now by microprobe analyses.
15. Tabular, spherulitic dikes intrude both the Gray and Black Members along planar fractures (Photo 7.35). This suggests that the intruded parts of the Onaping Formation were sufficiently competent for brittle failure and may indicate that these intrusions took place notably after the breccias were deposited.
16. Two-tailed Student's "t" test evaluations indicate that 2/3 of the elements analyzed for the fluidal-textured glass fragments and the Melt Bodies show a significant difference about their means at the 95% confidence level (Tables 7.8 and 7.12; the first point 10, this discussion). Either their genetic relationship can be questioned, or the degree of retention of original glass composition is in doubt.
17. The overall chemical composition of the Onaping Formation shows a progression, with some overlap, from relatively felsic compositions at the base, to relatively mafic compositions at the top (Figures 7.14a to 7.14e). There is a change from rocks with a calc-alkalic affinity to rocks with a tholeiitic affinity, which corresponds to the change from the Gray Member to the Black Member. This might have resulted from the emptying of a magma chamber, with the early erupted material from the top of the chamber being followed in one or more stages by more mafic material from lower down in a zoned chamber, or by intrusion of mafic magma into the bottom of the chamber (*see* Eichelberger 1980; Rice 1981; Huppert *et al.* 1982).
18. Chemical compositions of whole rock specimens of the Gray and Black Members show, at least locally: 1) major and minor trends which corre-

spond to successive samples in a stratigraphic section (Figures 7.16a to 7.16h); and 2) major breaks in trends which commonly correspond to adjacent units separated by a sharp contact (Figures 7.16a, 7.16c, 7.16e to 7.16h). The chemical composition of these members is not particularly erratic in element abundances and is reasonably well defined (Figures 7.14d, 7.14e). The above points are notable because one could predict there should be no ordered chemical relationships in a so-called heterolithic breccia which was produced from a single catastrophic event with no added magmatic component. It is not yet possible to resolve whether the well-defined inverse relationship between K_2O and Na_2O (Figures 7.16c, and 7.16d) is primary, or secondarily caused by the Sudbury Igneous Complex.

The following are what the author considers to be widely held perceptions that in some cases have originated from the study of a restricted area of the Onaping Formation, and subsequently have been assumed by geologists to be typical of the whole. The author presents his preferred interpretations.

1. *Perception:* The Onaping Formation is essentially an unstratified or unbedded pile of heterolithic breccia (Burrows and Rickaby 1930; Thomson 1957; Williams 1957; Stevenson 1972; Peredery 1972b; Brocoum and Dalziel 1974; Rousell 1975, 1981).

Preferred Interpretation: Bedding in the Onaping Formation is indicated by many units both on macroscopic (that is, members) and mesoscopic (that is, individual units of breccia) scales; some beds are defined by sharp contacts (Figures 7.4, 7.6 to 7.10; Photos 7.16, 7.17, 7.21, 7.26, and 7.30). Well-defined planar bedding has been recognized well within the Black Member (Photo 7.31). Prior to this study no bedding had been reported in the Onaping Formation, except by Cooke (1946) and, for the uppermost 200 m or so by Thomson (1957) and Peredery (1972a). Terms such as "zones", "lenses", and "depositional surfaces" have also been used (Stevenson 1961; Peredery 1972a, 1972b; compare with Peredery, Discussion of the Onaping Formation, this chapter).

2. *Perception:* The Onaping grades from coarse at the bottom to fine at the top (Burrows and Rickaby 1930; Dence 1972; Stevenson 1972; Beales and Lozej 1975; Rousell 1981).

Preferred Interpretation: The Onaping Formation has numerous units of breccia which collectively range from relatively coarse to relatively fine, and some of which, individually, display grading (Table 7.5; Figures 7.4, 7.9, and 7.11). The overall grading in the formation ranges from coarse at the bottom to fine at the top, only if the aberrations due to the individual units are not considered.

3. *Perception*: The Onaping Formation lacks substantial sorting within the heterolithic breccias (Thomson 1957; Dence 1972; Peredery 1972b).

Preferred Interpretation: The Onaping Formation has units of breccia in all members which show a high degree of sorting by fragment type, shape, size, abundance, or any combination of these characteristics (Tables 7.4 and 7.5; Figures 7.4, 7.7, 7.9 to 7.11; Photos 7.1, 7.7, and 7.14).

4. *Perception*: The Gray Member grades into the Black Member (Peredery 1972b; Beales and Lozej 1975; Muir 1983).

Preferred Interpretation: The Gray Member is locally gradational into the Black Member and is locally in sharp contact with the Black Member (Muir 1982; (Photo 7.25). Each member has its own lithologic characteristics such as types of glass fragments (Photos 7.11 to 7.13) and fairly distinct composition (Figures 7.14d and 7.14e). This suggests significantly different source material and may represent different magma sources, different depositional conditions, and/or a notable interval between eruptions. The sharp contact between the members, coupled with the association of chloritized shards which occur above it and throughout most of the Black Member, clearly serves to define the lower limit of the Black Member as the base of the shard-rich horizon. The lower limit of the Black Member has not been clearly defined by any previous worker, although Peredery (1972a, p.86, 124) noted chloritized shard-like fragments were absent in the Gray Member, but occurred above it in the Black Member (compare with Peredery, Discussion of the Onaping Formation, this chapter).

5. *Perception*: The Onaping Formation was deposited as a direct result of a single catastrophic event (French 1970, 1972; Dence 1972; Peredery 1972b; Rousell 1980).

Preferred Interpretation: The Onaping Formation was deposited as a result of multiple explosive events and numerous processes over a period of time much greater than that which could result from a single event. This is supported directly or indirectly by the above preferred interpretations and by the observations outlined in the second points 1 to 7, 9 to 13, 15, 17, and 18.

Based on the points presented in this discussion, the author concludes that:

1. the Basal Member formed largely from brecciated country rock as a result of one or more explosions, and its original matrix has locally been significantly modified by the plagioclase-rich granophyre and the Melt Bodies which are genetically related
2. the Gray and Black Members display sufficient features similar to those in some volcanic rocks that they likely formed from multiple explosive events involving magmas of different compositions, and likely involving some uncommon processes.

The author recognizes that many aspects of the Onaping Formation are problematical and that much more work is required to prove or disprove the above conclusions. The cause(s) for the initiation of the violent activity leading to the deposition of the Onaping Formation are enigmatic and have neither been addressed nor solved in any way in this discussion. Various aspects regarding the origin of the Onaping Formation and the Sudbury Structure, raised in this discussion and in that by W. V. Peredery (this chapter), are further considered in the chapter on the endogenic origin for the Sudbury Structure (Chapter 21, this volume).

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DISCUSSION OF THE ONAPING FORMATION

W.V. Peredery

Even though discussion on various aspects of the Onaping Formation continued from the earliest times, its volcanic origin was never questioned, or doubted, until the discovery of the evidence of shock metamorphism in the Sudbury area (Dietz and Butler 1964) and in the formation itself (French 1967). Since evidence of shock metamorphism is established in meteorite craters on the Earth such as the Meteor Crater in Arizona, and others, it was natural to extend the argument that the Sudbury Structure could be an ancient meteorite crater, and to re-examine the area from the new point of view. Much of the discussion that follows is based on the re-examination of the old and the new data from this new point of view. This is considered to be the most reasonable approach at this time, as to date no shock metamorphism has been established to be associated with normal volcanism.

Since the Onaping Formation has similarities to volcanic rocks, an attempt is made also to discuss some of the apparent volcanic aspects and interpretations made in the past.

BASAL MEMBER

Field evidence indicates that the granophyric rocks of the Sudbury Igneous Complex invade the Basal Member, locally causing discontinuities along its strike. The granophyric rocks close to the contact with the Basal Member carry abundant inclusions of rocks and breccia apparently derived from the Basal Member. The granophyric rocks are complex and at least 2 different phases have been recognized, both of which come in contact with the Basal Member.

The matrix of the Basal Member is recrystallized, inhomogeneous, and locally has igneous-looking textures. Stevenson (1963) and recently Muir (*see* his Discussion to this chapter) interpreted the igneous-looking textures as related to the Sudbury Igneous Complex and the contact as locally gradational between them. The sharp contact relationships between the Basal Member matrix and the granophyric rocks observed by the author in the course of this study do not agree with the above interpretation and suggest there may be a different explanation. This is based on the observation that the igneous-textured matrix is sporadically distributed in the Basal Member and occurs associated with, or is present inside, various country rock fragments not only in the Basal Member but also in other members of the Onaping Formation. This certainly is not indicative of magmatic permeations that could be attributed to the granophyres. The author thinks that the igneous-textured matrix in the Basal

Member is probably related to the peculiar character of brecciation or to shock metamorphism itself.

In spite of this, there is the possibility that the Basal Member matrix has been affected to some degree by metasomatism related to the granophyres. The presence of perthitic and antiperthitic feldspars in the metamorphic-textured matrix suggests both potash and soda metasomatism. This is in agreement with the generally sodic and potassic nature of the matrix. In other cases, the highly siliceous character of the matrix suggests there may have been silicification of it.

The original matrix of the Basal Member was probably a highly pulverized mixture of country rock fragments (Stevenson 1960). It has been noted (Muir and Peredery, Chapter 7, this volume) that the Basal Member matrix is apparently richer in mafic minerals than the majority of the enclosed inclusions. This suggests that perhaps some magnesia and iron have been introduced also. As an alternative, the author would suggest that this apparent enrichment in mafic minerals is perhaps related to the competency of rocks during brecciation and pulverization. Generally, the more mafic rocks are less competent than the felsic ones, and therefore, would tend to be more pulverized and hence could contribute more mafic minerals to the matrix than the more resistant felsic rocks. This is perhaps one of the reasons for the apparent paucity of mafic country rock inclusions in the Basal Member.

The difference in the relative abundance of lithological constituents of the Basal Member between the North, East, and South Ranges is probably a reflection of the provenance of these rocks. On the South Range, the dominant metasedimentary rocks in the Basal Member could have been derived from the Huronian Supergroup, and the minor granitic rocks could have been derived from the Huronian granitic intrusions. On the East and North Ranges, the Basal Member is composed of various mixtures of granite, gneiss, and metasedimentary rocks. The provenance for the granites and gneisses could be the Superior basement rocks, but the provenance for the metasedimentary rocks is more problematical. These rocks were either derived from the distant Huronian Supergroup, or were locally derived from a Huronian cover. Since mixing of basement and metasedimentary rocks occurred throughout the North and East Range Basal Member, it is not difficult to visualize that these mixtures were probably locally derived and hence imply that there was a veneer of Huronian rocks covering much of the Sudbury Structure. This is supported by outliers of the Huronian rocks found to the northwest and north of the Sudbury Structure.

On the South Range, lenses of Basal Member occur also in the overlying Gray Member. Stevenson (1960) interpreted these lenses to be tectonically emplaced from the Basal Member. Although this is a pos-

sibility for some of them, the author is inclined to interpret these lenses as slumped material from the crater wall.

The Basal Member reflects not only the provenance of the rock types contained within it, but also the mechanism of brecciation. Abundant evidence of shock metamorphism in the breccia fragments (French 1967, 1968, 1972; Peredery 1972a, 1972b) is indicative of the source of energy that caused brecciation. Since the shock features are of a similar character in the country rock fragments in all the members, they will be discussed under one heading later.

The absence of glass fragments in the matrix of the Basal Member, and the abundant presence of these fragments in the overlying Gray Member indicate a sudden change in the depositional regime.

GRAY AND BLACK MEMBERS

Stratification

Although each member of the Onaping Formation is composed of heterolithic rock materials, each member is distinct in itself. The Onaping Formation is thus layered on a gross scale.

In general, the Gray Member can be described as a chaotic assemblage of a variety of glasses and country rock fragments. Bedding is generally absent, except that on a gross scale, the Gray Member can be said to have a crude sorting. On a local scale, recognizable units could be established, but they lack continuity and their contacts with other units are imperceptible and gradational. Trends of high energy deposition are indicated by abundant and large boulders of various country rocks in the Gray Member, but they have no lateral continuity. Thus, in general, it could be said that the bulk of the Gray Member was a high energy, rapid accumulation of largely unsorted debris.

In the upper 20 to 50 m of the Gray Member, the size of the country rock fragments decreases, their total abundance decreases, and the glassy fragments become either gradationally or rapidly fine grained and shard-like in shape. From the base upward, this is the first notable change that can be defined as a horizon with lateral continuity (Burrows and Rickaby 1930); it has been traced practically around the whole of the Onaping Formation (Stevenson 1972; Peredery 1972a). Above this horizon, a renewed high energy cycle of deposition is evident, and marks the lower contact of the Black Member (Peredery 1972a).

Recently, bedding with distinct sharp contacts was observed in the upper part of the Gray Member (Muir and Peredery, this volume). In this discussion, the author is inclined to think that the bedding probably represents a high energy, local erosional feature. The bedding has limited lateral continuity, and shows evidence of erosion of some of the fragments, sorting of

fragments, and is in many aspects similar to the discontinuous bedding noted in the Black Member (Peredery 1972a).

The Black Member is characterized by carbonaceous material in the matrix giving the rock a dark colour. Discontinuous country rock and glass boulder trends are locally present at the base of the member and stratigraphically higher up, and discontinuous bedding, although not common, has been noted throughout the member (Peredery 1972a, 1972b). In general, the lower half of the member exhibits the same chaotic assemblage of glasses and country rock fragments as in the Gray Member, but in the upper half, a noticeable decrease in the average size of fragments occurs; the member becomes progressively finer grained upward so that the contact with the overlying Onwatin slates is gradational. Reworking of materials during deposition appears commonly to have produced discontinuous gritty mud beds in the uppermost stratigraphic levels.

In general, the absence of bedding in the bulk of the Gray Member suggests that it was one gigantic depositional event. The presence of bedding and concentration of boulders at the base of the Black Member indicate a later period of high energy deposition after the Gray Member was laid down. On the basis of the above evidence, Peredery (1972b) proposed the tsunami-wave action to account for the rapid deposition and thick accumulation of the debris in the Black Member. Evidence of reworking of this debris, especially in the stratigraphically higher levels, supports this proposal.

The apparent lack of stratification in the Onaping Formation, except on gross and local scales, is inconsistent with normal volcanic deposits, including the interpretation of the formation as a glowing avalanche or ash-flow sheet (Williams 1957; Stevenson 1972). Glowing avalanches or ash-flow sheets are well known for their stratified character; the Onaping Formation stratification is of such magnitude and on such a gross scale that to the authors knowledge, no counterpart is known to exist in volcanic terrains. On the other hand, at meteorite impact sites, the fallback debris, deposited in the crater and outside of it, shows little if any stratification, and is commonly heterolithic in character. In this context, the Gray and Black Members are analogous to fallback breccia.

Glasses

Welded textures among glassy fragments are typical of the glowing avalanche deposits, but such textures are practically absent in the Onaping Formation. Stevenson (1972) attempted to demonstrate welding among glassy fragments, but his illustrations indicate an open framework among fragments, typical of the bulk of the Gray and Black Members. Some welding between

various fragments and glasses, however, is present and is particularly evident in bomb-shaped bodies scattered throughout the Onaping Formation. The collapsed pumice features and polygonal jointing typical of ash-flow sheets are not obvious in the Onaping Formation. Some fluidal glasses superficially resemble collapsed pumice fragments, but their heterogeneous character, in particular, is unlike the normal collapsed pumice material.

The truncation of flow lines in fluidal glasses is common in the Gray and Black Members and demonstrates that the glassy material has been fragmented either before or during the deposition. Fragmented glasses are not typical of glowing avalanche deposits.

Petrographically and chemically, most of the fluidal glasses in the Gray and in the Black Members are inhomogeneous. These glasses commonly contain fragments of rocks and minerals and have no phenocrysts. The fluidal glasses are composed of finely recrystallized material with fluidal lines or domains composed of variable proportions of felsic and mafic products. This is unlike the volcanic glasses with flow lines in which the devitrification products have little variation from one flow line to another. In a study on flow-lined volcanic material, it has been demonstrated that there is no significant difference in the chemical composition between the flow-lined domains (Marénina 1966). The difference is mainly in the state of oxidation of iron, but the total iron remains constant.

The electron microprobe analyses on the fluidal glasses yield a wide array of compositions in any given sample and support the petrographic observations of heterogeneity of these glasses (Peredery 1972b, 1972a-Table 12). In terms of SiO_2 , the values range from 52.78 to 69.67% among samples, and in a given sample, there can be up to 8% oxide weight variation. The Al_2O_3 values range from 2.88 to 20.29%, with up to 8% oxide weight variation in some samples. Total iron, calculated as FeO, ranges from 0.50 to 16.02%, with up to 5% oxide variation in some samples. MgO values range from 1.22 to 12.72%, with up to 7% oxide variation in some samples, and CaO values range from 0.34 to 12.45%, with up to 5% oxide weight variation in some samples. Na_2O values range from 0.52 to 11.63%, and some samples have up to 5% oxide weight variation. Interestingly, some samples with constant Na_2O values exhibit considerable variation in SiO_2 , Al_2O_3 , FeO, MgO, and CaO. The K_2O values range from 0.14 to 7.52%, and in individual samples, the variation is surprisingly rather small, about 3% oxide weight.

Such variation in the oxides cannot be attributed to alteration, as the variation does not fit into any recognizable pattern. As noted by Stevenson (1972) and Peredery (1972a), alteration of glasses in the On-

aping Formation results in the development of feldspathic rims, and chlorite and sphene are formed in the interior of glass fragments.

In view of the above data on the fluidal glasses, the whole rock analytical approach taken by most of the early investigators and recently by Muir (Discussion in this chapter) should be viewed with caution. Such whole rock analyses would not eliminate the effect attributable to the fine country rock inclusions and xenocrysts in the sample analyzed. Such an approach gives, at best, only an approximation to the averages of a variety of inhomogeneous glasses and camouflages the real problem of glass genesis.

In conclusion, the petrographic and chemical heterogeneity of fluidal glasses in the Onaping Formation probably represents an original feature and is atypical of volcanic glasses. In the meteorite impact theory, these inhomogeneous fluidal glasses represent shock-melted country rocks that become quenched in their flight through the atmosphere. Quenching is, therefore, responsible for preserving inhomogeneities in molten materials that did not have a chance to become homogenized. Shock melting is estimated to have occurred at pressures > 500 kbars (French 1967).

Another variety of glass common in the Onaping Formation is a complex glass (Peredery 1972a; Muir and Peredery, Chapter 7, this volume). Complex glasses, together with the fluidal glasses discussed above, account for the bulk of the glasses in the formation. Mineralogically and texturally, the complex glasses consist of devitrified or recrystallized domains up to several mm in diameter of quartz or feldspar compositions, or less commonly, spherulitic mafic minerals that chemically correspond to sub-calcic augite (Peredery 1972a). They are generally similar to some of the highly shocked country rocks with devitrification textures. One other feature that both the complex glass and the country rock fragments share is the presence of planar elements in quartz. These planar elements are far more common in the country rock than in the complex glass fragments. Nevertheless, the presence of planar elements in both is significant from the genetic point of view because it shows that the country rock and complex glass fragments have undergone metamorphism, but to different degrees. Complex glasses, of the type found in the Onaping Formation, have not been reported in the literature on normal volcanic rocks. French (1967) interpreted these glasses to have formed by shock metamorphism at the maskelynite stage.

In general, the vesicular and plastically deformed character of many of the complex glasses indicates that they attained a high temperature. These high temperatures could also act to destroy the original features of shock by devitrification and recrystallization.

Country Rock Fragments

Country rock fragments are similar to those in the Basal Member or Melt Bodies. They vary in size from a few mm up to 100 m in diameter and are present throughout the Gray and Black Members. It is estimated that at least 10% of the total volume in both Members is represented by country rock material, and that locally, especially in boulder-rich horizons, up to 30% can be country rock (Peredery 1972a).

Country rock inclusions in volcanic rocks have been described in the literature. The action of magma on the xenoliths or adjacent country rocks is described mainly as thermal effects (Hawkes 1929; Knopf 1978; Larsen and Switzer 1939; and Steiner 1958). A description of the pressure effects is generally lacking.

Shock Metamorphism

Shock pressure features are ubiquitous and abundant in the country rock inclusions throughout the Onaping Formation. However, with the increase in shock pressure, temperature effects become important; at extremely high pressures, the temperature effects become dominant and commonly obliterate the pressure features by recrystallization and melting. The shock pressure and temperature effects have been collectively referred to as shock metamorphism by French (1967). Following the scheme of French (1967, 1968, and 1972) and others, intensities of shock metamorphism in the Onaping Formation can be roughly grouped in accordance with the pressures and temperatures present at the time of their formation as follows:

- I. low pressure-low temperature (50 to 150 kb, up to 200°C) features such as decorated planar elements in minerals such as quartz, feldspars, pyroxenes, and apatite
- II. high pressure-intermediate temperature (150 to 380 kb, up to 450°C, maskelynite stage of shock metamorphism) features such as highly disordered crystal lattices, which can be identified by the subsequent devitrification textures in minerals, as in the complex glasses and country rock fragments
- III. high pressure and temperature (380 to 500 kb, up to 1600°C) effects such as partial melting of minerals including sphene and zircon; vesiculation, plastic deformation, and partial melting of rocks to produce flow-banded heterogeneous glasses (fluidal glasses)
- IV. intense high pressure and temperature (> 500 kb, > 1600°C) effects leading to total melting of country rocks to produce crystalline igneous-textured rocks known as impact melt, or finely quenched fluidal glasses

In addition, some country rock fragments have shatter cones similar to those found in the Footwall

rocks (Dietz 1972). Since shatter coning is an integral part of shock metamorphism, their presence in the Onaping Formation is as predictable as all of the other shock features.

The state of preservation of shock-metamorphic features in the Sudbury area varies considerably and depends on the regional metamorphism, tectonism, the thermal effects related to the Sudbury Igneous Complex magmatism, and the heat within the Onaping Formation itself. Under these conditions, the high pressure polymorphs of quartz, such as coesite or stishovite, would be recrystallized, and for these reasons would not be expected to be found in the Sudbury Structure. On the South Range, the effects of the Penokean Orogeny tended to destroy the shock features. Recrystallization obliterated the planar elements, but evidence of devitrification in minerals is locally well preserved in the relatively less deformed rocks.

Recognition of a whole spectrum of pressure and temperature effects in the country rock fragments creates a serious problem for the volcanogenic interpretation of the Onaping Formation. Firstly, shock-metamorphic features are not associated with normal volcanism. Even in the most violent volcanic eruptions, the highest pressures attained are about 5 kb (Gorshkov 1959), an order of magnitude less than those required to produce the weakest shock effects. As pointed out by French (1967) and other investigators, the near-surface crust is not capable of sustaining great pressures due to volcanic or tectonic activity. In other words, failure occurs at much lower pressures than those required to produce shock metamorphism.

The petrographic evidence of shock metamorphism in the Onaping Formation or in the Sudbury Structure is similar to that in the well known meteorite impact sites such as the Ries Structure in Germany and the Meteor Crater in Arizona (Kieffer 1971; Nininger 1954). In the Meteor Crater, fragments of meteorite are scattered around the rim of the structure (Mead *et al.* 1965). The high temperature shock features in the Onaping Formation, such as fluidal glasses, have their counterparts in the heterogeneous glasses, so-called *fiadlen*, in the Ries Structure, or the *lechatelierite* glasses of the Meteor Crater (and many other proposed impact structures). The heterogeneous character of the glasses in the Gray and Black Members is unusual from the volcanogenic point of view, but they are similar in character to those found at other impact craters.

Carbonaceous Matrix

If the Black Member is considered to represent a rapidly deposited sequence, then the presence of carbonaceous material throughout the matrix of the member extending laterally over a distance of at least 60 km and vertically about 800 m is most unusual. The sugges-

tion by some investigators (Burrows and Rickaby 1935) that the carbonaceous material developed by the reduction of gases during fumarolic activity, does not agree with its present distribution pattern, nor its abundance in the Black Member. Besides, the numerous feeder structures presumably required for such exhaustive fumarolic activity are absent or lacking in the Onaping Formation. The origin of the carbonaceous material is not certain.

Melt Bodies

Melt Bodies with chilled or chilled-brecciated margins together with the development of apophyses of fluidal glass indicate these rocks flowed like lavas. Lenses and dikes of Melt Bodies also intrude the Gray Member and, relatively rarely, intrude the lower part of the Black Member. Inclusions in the Melt Bodies are of the same lithological types and have a variety of shock features as in the Basal, Gray, and Black Members.

In the literature, the chemical data on the Melt Bodies show pronounced variability ranging in composition from rhyolite to andesite and include some peculiar lime-poor rocks of quartz keratophyre affinity (Burrows and Rickaby 1930; Thomson 1957; Cooke 1946). Investigations by Peredery (1972a, 1972b) confirmed that the Melt Bodies are variable and range from rhyolitic to andesitic compositions commonly in one and the same body. Peredery argued that rapid crystallization or quenching in the Melt rocks probably resulted in the preservation of primary heterogeneities. Furthermore, with rapid quenching there would be little time available for assimilation of inclusions. It is considered unlikely that the melt was originally a homogeneous liquid that was so extensively contaminated as to give rise to rocks of rhyolitic to andesitic compositions. Thus, although assimilation may have played an important role in the final composition of Melt rocks, their extreme chemical variability is probably not a result of contamination but is a primary feature. Such rocks of variable compositions have not been reported in normal volcanic terrains.

Interpretation of the Melt Bodies is controversial. Stevenson's (1963) interpretation of the melt as a chilled phase of the granophyre of the Sudbury Igneous Complex posed quite a problem for the volcanologists as it eliminated the feeder structures for volcanism in the Onaping Formation. To solve this problem, Stevenson and Stevenson (1980) proposed that the feeder for the Onaping Formation could be somewhere outside the Sudbury Structure. Peredery (1972a) has proposed that the Melt Bodies and fluidal glasses are related. The fluidal glasses that are directly related to the chilled and chilled-brecciated Melt Bod-

ies, and those that occur as distinct bodies or fragments in the Onaping Formation have similar megascopic, microscopic, and chemical characteristics. In fact, chemically, all show heterogeneities. This in itself suggests that the glasses originated from a heterogeneous material.

The heterogeneous character of Melt Bodies coupled with their close association with heterogeneous glasses and shock metamorphism, strongly suggest that the Melt Bodies could be impact melts. Such melts are produced coincident with the highest grade of shock metamorphism which can lead to the total melting of target rocks. Their crystalline or quenched state is a product of the subsequent cooling history. The surface target rocks were probably Huronian sediments, but petrologic mixing calculations indicate the best approximations are obtained using mixtures of granites, gneisses, and gabbroic rocks (see Table 1). In this table, a mixture consisting of rocks from the Birch Lake Pluton (8%), Creighton Pluton (51%), gneisses (40%), and gabbroic Footwall rocks (1%) approximates reasonably well the Melt Body (DW443-70) from the North Range. Perhaps, additional data on the basement rock may improve the calculated approximations in the future.

In summary, the field evidence, petrography, and petrochemical data on the Melt Bodies are consistent with the concept that they could represent molten country rocks or impact melt caused by the meteorite impact. Petrological mixing exercises suggest that the country rocks involved in melting were mainly the Superior Basement and the granitic rocks emplaced in the lower stratigraphic sequence of Huronian sedimentary pile.

A model for the evolution of the Onaping Formation and the Sudbury Structure is presented by Peredery and Morrison (Chapter 22, this volume).

TABLE 1: COMPARISON BETWEEN CHEMICAL COMPOSITION OF A MELT BODY FROM DOWLING TOWNSHIP, AND A CHEMICAL COMPOSITION CALCULATED FROM A PETROLOGICAL MIXTURE OF BASEMENT ROCKS IN THE SUDBURY AREA (AFTER PEREDERY 1972A, P.291).

	Melt Body (DW443-70)	Calculated Rock Mixture	Difference
SiO ₂	69.60	69.61	-0.01
Al ₂ O ₃	13.31	13.37	-0.06
TiO ₂	0.50	0.38	0.13
FeO	3.73	3.79	-0.06
MnO	0.08	0.03	0.05
MgO	1.66	1.19	0.47
CaO	2.36	2.58	-0.22
Na ₂ O	3.54	3.64	-0.10
K ₂ O	3.06	3.02	0.05

CHAPTER 7

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CHAPTER 8

Onwatin and Chelmsford Formations

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ABSTRACT

The contacts between the Onwatin Formation and the underlying Onaping Formation and the overlying Chelmsford Formation are gradational and conformable. The Onwatin Formation is poorly exposed; the approximate thickness is 600 m. The formation consists mainly of carbonaceous and pyritic argillite and siltstone with minor wacke. The Vermilion Member is a local sulphide-bearing carbonate chert unit that occurs near the base of the formation; the average thickness is 43 m. The bulk of the formation represents pelagic sediments that were deposited in a restricted basin with anoxygenic bottom waters. The wacke beds were deposited by turbidity currents. The Vermilion Member is interpreted to be a sedimentary-exhalative deposit.

The Chelmsford Formation, approximately 850 m thick, is a remnant of a unit that was once thicker and

more extensive. The formation consists of turbidite beds with certain Bouma divisions. Division A is the most common division (present in 99% of the beds) and thickest (mean = 1.12 m), and consists of poorly sorted, commonly graded arkosic wacke. Division B is poorly developed and does not appear to be a natural division of the formation. Division C occurs in 14% of the beds, has a mean thickness of 0.3 m, and consists of fine- to very fine grained sandstone. Division D occurs in 68% of the beds, has a mean thickness of 0.15 m, and consists of very fine grained sandstone, siltstone, and argillite. Sedimentary structures include concretions, fragments, channels, current marks, ripples, convolute laminations, load structures, and possible biogenic structures. The formation represents a proximal turbide sequence deposited in an elongate trough having a southwesterly paleoslope. The source area was a tonalite terrain such as that to the northwest of the Sudbury Basin.

INTRODUCTION

The sedimentary rocks within the Sudbury Basin are divided into 2 units, the Onwatin Formation and the overlying Chelmsford Formation (Coleman 1905). The contact between the 2 formations is gradational and conformable, as is the contact between the Onwatin Formation and the underlying Onaping Formation.

The Onwatin Formation weathers relatively rapidly and is poorly exposed. The formation lies beneath a topographic low which has the shape of an elliptical ring 5 km wide, and is largely covered by surficial deposits. The Chelmsford Formation is exposed in a series of northeasterly trending anticlinal ridges. This formation occupies an elliptical area, surrounded by the topographic ring, that extends 33.8 km in a northeasterly direction and 7.2 km in a northwesterly direction.

ONWATIN FORMATION

The Onwatin Formation is named after a small lake (a widening in the Vermilion River) at the northeastern end of the Sudbury Basin. The formation does not outcrop in the vicinity of the lake; the best exposures are in the southwestern part of the basin, and most are of the bottom or top parts of the unit. A type section has not been defined and outcrops display only a few m of continuous exposure. The formation consists essentially of carbonaceous and pyritic, massive to laminated argillite and siltstone together with minor wacke; a local carbonate-chert unit occurs at the base (Vermilion Member). General descriptions of the formation are given by numerous investigators including Coleman (1905), Burrows and Rickaby (1930), Thomson (1957), and Beales and Lozej (1975). Martin (1957) described the Vermilion Member. The most detailed study of the Onwatin Formation, mainly geochemical in nature, was made by Sadler (1958). Arengi (1977) reviewed existing information and provided additional geochemical data.

Coleman (1905) suggested that the Onwatin Formation is approximately 1100 m thick. Arengi (1977) used outcrop widths and surface dips of approximately 30° to obtain a thickness of as little as 900 m in the North Range and as much as 1410 m in the South Range. These values appear to be excessive because the formation is folded, and Rousell's (1975) estimate of 600 m is believed to be more realistic.

The contact between the Onaping Formation (Black Member) and the overlying Onwatin Formation is gradational, and hence is difficult to define. Sadler (1958) identified a transition zone that is carbonaceous, massive, and very fine grained. Arengi (1977) assigned this zone to the Onaping Formation

because the chemical composition resembled that of the Black Member more than the Onwatin Formation. A decrease in grain size and abundance of rock fragments, and an increase in quartz grains and matrix up-section has been measured and continues across the contact. Arengi (1977) arbitrarily assigned rocks to the Onaping Formation if clasts are present and to the Onwatin Formation if they are absent. Chemical changes across the contact are as follows (Sadler 1958; Arengi 1977): SiO_2 , Al_2O_3 , and Fe_2O_3 increase, and CaO and MgO decrease up-section; the $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratio is higher in the Onaping Formation and the MgO/CaO ratio is higher in the Onwatin Formation; and Cr and Sr values are relatively high in the Onaping Formation while Ni, Cu, Pb, Zn, Ag, and V values are relatively high in the Onwatin Formation.

Martin (1957) applied the name "Vermilion Formation" to a distinct carbonate-chert facies that overlies the Onaping Formation and hosts the ore in the Vermilion and Errington Mines (see Rousell, Chapter 9, this volume). Arengi (1977) relegated the unit to a member of the Onwatin Formation because of lateral discontinuity. Figure 8.1 is a diagrammatic representation of the Vermilion Member. The average thickness of the member is approximately 43 m. A massive, siliceous, and carbonaceous argillite (0 to 30 m thick), containing fine-grained and disseminated grains and thin layers of pyrite, occurs at the base of the member; the argillite was supposedly partly replaced by the overlying carbonate rocks from the top down (Martin 1957). The argillite may be thin or absent where the carbonate is thick and as the carbonate thins, the argillite thickens. The lateral facies equivalent of the member consists of massive argillite overlain by laminated argillite and siltstone (Arengi 1977). The basal argillite is not part of the carbonate-chert facies and should be excluded from the Vermilion Member and is indicated as such in Figure 8.1. The carbonate rock hosts most of the ore; it may be up to 30 m thick, ranges from fine to coarse grained, locally exhibits a pisolitic texture, and may be prominently layered (see Photo 8.1 and photograph in Thomson 1957, p.50). A zone of cherty carbonate rock, approximately 6 m thick, marks the gradation from carbonate rock to chert breccia. The chert breccia is replaced by carbonate and, locally, this process is almost complete. The chert breccia, approximately 3 m thick, consists of black chert fragments that are generally < 5 cm in length. The fragments are set in a matrix of white recrystallized chert. The uppermost unit of the member is approximately 6 m thick and consists of interbedded argillite, limestone, and dolostone. Chert breccia and mineralized dolostone are exposed at the Errington Number 1 shaft (see Rousell, Chapter 9, this volume, Figure 9.1). Several drillholes have penetrated rocks that are apparently equivalent to those of the Vermilion Member in the mines (Arengi 1977). Three drillholes in the

North Range encountered argillaceous limestone 1 to 4 m thick (northeast of the metagabbro sill and southwest of the Proulx Occurrence, *see* Rousell, Chapter 9, this volume, Figure 9.1). In the South Range, a drillhole (between the Foisey and Papineau Occurrences, *see* Rousell, Chapter 9, this volume, Figure 9.1) penetrated approximately 30 m of argillaceous limestone and cherty limestone; and 2 other drillholes, southwest of the above hole and northwest of the Errington Number 3 shaft (*see* Rousell, Chapter 9, this volume, Figure 9.1), penetrated 2 m of the same rock types.

According to Arengi (1977), the Onwatin Formation consists of the following rock types (exclusive of the Vermilion Member) in order of abundance: argillite, fine-grained siltstone, silty argillite, coarse-grained siltstone, and greywacke. The argillite is laminated and consists of quartz, sericite, clays, and some carbonate and mica. The silty argillites have the same composition as the argillites and, in addition, contain scattered silt-size quartz grains. Carbonaceous material is microconcretionary to blade-like in form, and imparts a dark colour to the argillites. The siltstones are composed of quartz, plagioclase, micas, and matrix and have a lower carbonaceous content and hence are lighter than the argillites. Laminae are, in general, 5

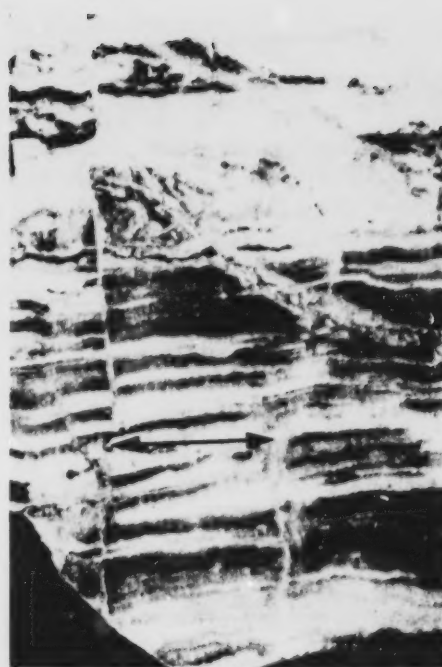


Photo 8.1. Layered carbonate rock from the dump at Errington Number 2 shaft. Bar is 5 cm.

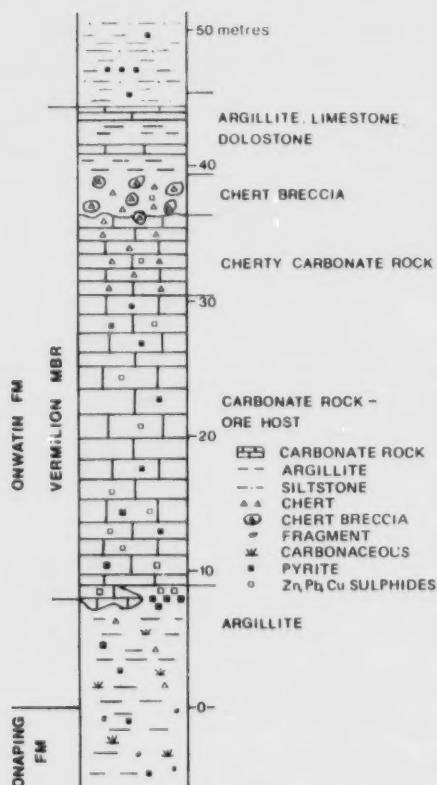


Figure 8.1. Diagrammatic representation of the Vermilion Member (after Rousell 1983).

mm or less in thickness; graded layers up to 15 cm thick occur locally. Pyrite is abundant and it occurs as disseminated silt-size grains, as clusters of cubes, as lenses up to 20 cm thick, and along cleavage planes. Minor greywacke layers are present in the Onwatin Formation; these layers occur in outcrop and in drill core. Three greywacke layers outcrop in the southwestern part of the basin (Arengi 1977). The estimated stratigraphic position of these layers below the base of the Chelmsford Formation and their respective thicknesses are: 750 m and 4 m; 550 m and 10 m; and 200 m and 4 m. The layers are similar in composition to greywacke in the Chelmsford Formation. Sadler (1958) reported several greywacke layers, < 0.3 m thick, in drillcores from Bleazard Township.

Estimates of the range of the total carbon contents of the Onwatin Formation vary and include: Coleman (1905) from 6.8 to 10%; Burrows and Rickaby (1930) from 0.30 to 3.35% (4 samples); Beales and Lozej (1975) from 7.12 to 3.39% (5 samples); and Arengi (1977) from 0.63 to 7.72% (7 samples). The formation contains carbonate minerals; thus the carbonaceous content must be based on analyses of free carbon. According to Arengi (1977), the free carbon content (7 samples) ranges for 0.26 to 4.05%. Metamorphism has locally concentrated the carbon into anthraxolite veins, a lustrous black material that contains approximately 95% carbon (Burrows and Rickaby 1930). Arengi (1977) examined carbon concentrates

from argillites under the scanning electron microscope. The carbon occurs as elongate segmented structures, either as individuals or clots, that resemble modern and fossil algal and fungal filaments.

Secondary carbonate minerals are common in the Onwatin Formation, particularly in the South Range, and are either disseminated, or, fill fractures, or, are the matrix of breccias. Numerous breccia zones cemented by quartz and brown carbonate occur in drill cores from Fairbank Township. Local, pale pink carbonate was identified as manganodolomite by X-ray powder photography (Sadler 1958).

The bulk of the Onwatin Formation represents pelagic sediments; the Vermilion Member and enclosed mineralization is probably a sedimentary-exhalative deposit. The sediments were deposited in a deep, restricted basin and the abundant carbonaceous material and pyrite suggest that bottom waters were stagnant and anoxic. The carbonaceous material may have been derived from floating algal mats. A supposed chemical similarity between the Onwatin Formation and the Onaping Formation led Sadler (1958) to the conclusion that the former was derived from the latter. In actual fact, the Onaping Formation is chemically and lithologically heterogeneous (Peredery 1972) and cannot be equated with the composition of the Onwatin Formation.

According to Arengi (1977), chemical and textural changes across the Onaping-Onwatin contact indicate that the Onwatin sediments were not derived from the Onaping Formation, but instead had an extra-basin source. The Onwatin Formation represents a time of pelagic deposition sandwiched between the violent events associated with the deposition of the Onaping Formation and the rapid deposition of turbidite beds of the Chelmsford Formation. The presence of minor greywacke units and slumped layers in the Onwatin Formation suggest that the events leading to the deposition of the Chelmsford Formation were initiated, albeit weakly, in Onwatin time.

CHELMSFORD FORMATION

The preserved thickness of the Chelmsford Formation is approximately 850 m. The formation represents the remnant of a unit that was originally thicker and more extensive. A type section of the formation has never been defined, a complete section is not exposed at any single locality, and the lack of marker beds precludes correlation from place to place. Burrows and Rickaby (1930) recognized that the sediments were deposited rapidly and Williams (1957) was the first to ascribe deposition by turbidity currents. Detailed descriptions of the formations are given by Cantin (1971) and by Rousell (1972). Cantin and Walker (1972) evaluated

current directions and the nature of the deposition basin.

The contact between the Chelmsford Formation and the underlying Onwatin Formation (exposed in lot 3, concession VI, Balfour Township, and lot 3, concession I, Dowling Township) is defined as the base of the first greywacke layer that marks the transition from argillite and siltstone and minor greywacke to mainly greywacke with minor argillite and siltstone.

Beds and Bed-Division

A turbidite bed represents the deposit of a single turbidity current (Bouma 1962; Walker 1967). A complete turbidite bed may be divided into 5 divisions:

A-graded sandstone

B-parallel-laminated sandstone, may be graded

C-current ripple-laminated fine-grained sandstone, may be convoluted

D-indistinct parallel lamination in very fine grained sand to silty pelite

E-pelite

Rousell (1972) made a detailed study of 7 sections of the Chelmsford Formation that contained a total of 188 beds. The formation displays a rhythmic sequence of beds and bed-divisions that can be related to some of the divisions of Bouma (1962). For all sections, divisions A, C, and D are present in 99%, 14%, and 68% of the beds, respectively. Division B contains poorly laminated layers and lithologically resembles division A. Division B is not well developed, does not appear to be a natural division, and is included with division A. Division E was not recognized in the formation. The beds range in thickness from 0.04 to 5.2 m and the average is 1.23 m; the 0.2 to 0.4 m interval has the greatest frequency (16%). There are no consistent changes in bed thickness upward in the sections.

Division A is the thickest division and is present in almost all beds; 15% contain division A only. The mean thickness is 1.12 m and the maximum is 5.2 m; the interval 0.2 to 0.4 m has the greatest frequency (17%). Division A consists of dark grey, poorly sorted, commonly graded greywacke (arkosic wacke of Pettijohn *et al.* 1972, p. 158). An average volume percentage of constituents is: quartz (29.5%), plagioclase (22%), microcline (1.5%), light-coloured matrix (15%), black matrix (11%), chlorite (19%), muscovite and biotite (1.5%), and accessory minerals (0.5%). Plagioclase, generally twinned and unaltered, ranges in composition from An_{12} to An_{36} and has a mean of An_{32} . The light-coloured matrix consists of finely comminuted quartz and feldspar and the black matrix consists of carbonaceous material. Chlorite is oriented parallel to the cleavage and was formed by metamorphism. Planar features, characteristic of shock

metamorphism, are absent in quartz and feldspar. The contact between division A and underlying divisions is always abrupt (Photo 8.2) although flame structures may penetrate division A. Division A grades into division B, whereas the contact with divisions C or D is generally sharp; load structures may cause the contact to be undulatory or irregular. The thicker the division A, the more prevalent the grading, the coarser the grain size at the base, and the greater the range in grain size from bottom to top. For example, when division A exceeds 2 m in thickness, 80% of the layers are graded and 38% have granule size or larger material at the base; when division A is < 0.25 m thick, 31% of the layers are graded, and only 4% begin with granule size or larger.

Division C occurs in only 14% of all beds and consists of buff-coloured, fine- to very fine grained sandstone. Ripples, climbing ripples, and small-scale crossbedding are common (Photo 8.3). The mean thickness is 0.3 m and the maximum is 1.15 m; 60% of division C layers are in the thickness interval 0 to 0.2 m. An excellent example of division C occurs in a roadcut on the south side of Highway 144 located at the first exposure immediately east of the Vermilion River bridge.

Division D is common, occurs in 68% of the beds, and is composed of very fine grained sandstone, siltstone, and argillite. Convolute laminations are locally present. The upper contact is sharp; and flame structures commonly penetrate the overlying division A; the underlying contact is generally abrupt and modified by load structures. The mean bed thickness is 0.15 m and the maximum is 1.9 m; 79% of division D layers are in the thickness interval 0 to 0.2 m.

Sedimentary Structures

The Chelmsford Formation displays a variety of sedimentary structures including concretions, fragments,

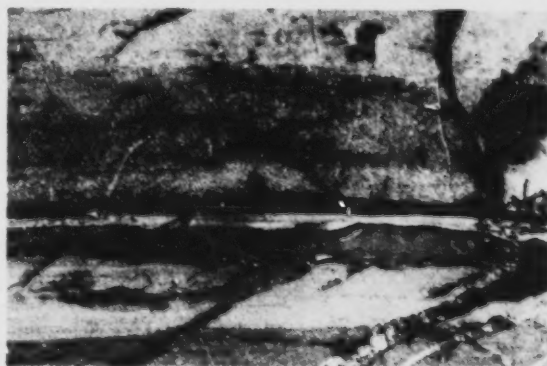


Photo 8.2. Sharp contact between division A and division C of underlying bed. Division C contains scours. Vermilion River south of Highway 144.

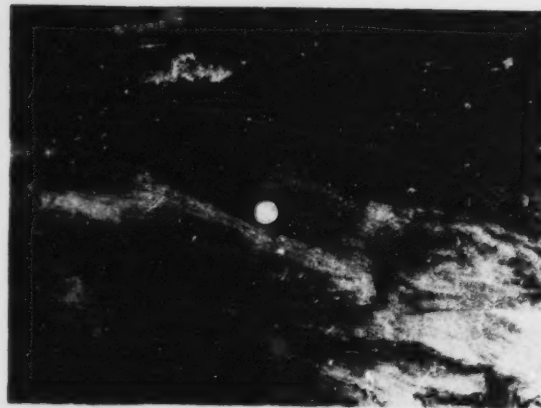


Photo 8.3. Climbing ripples, division C. Vermilion River south of Highway 144.



Photo 8.4. Concretions. Highway 144.

channels, current marks, ripples, convolute laminations, load structures, and possible biogenic structures.

Concretions (Photo 8.4) are common, occur in about 26% of the beds, and are richer in iron and carbonate than the matrix that encloses them. These concretions have a variety of shapes including spherical, ellipsoidal, lenticular or pipelike bodies; or the concretions may resemble coalesced beds. Most concretions occur in division A, some are in divisions B and C, but they are never found in division D. Concretions have been observed which straddle the contact between the A divisions of 2 adjacent beds and divisions A and C of 2 adjacent beds. A concretion truncated by a channel indicates that the concretion formed soon after the deposition of the bed.

Approximately 17% of the beds contain rock fragments. Most consist of slabs of laminated argillite and siltstone that resemble either the Onwatin Formation or division D of the Chelmsford Formation. Sev-

eral are over 3 m in length and 1 slab 3 m by 1 m by 0.28 m, is oriented normal to the bedding plane. Apparently, the slab was tilted on its side when buried. Some slabs are distorted and this probably took place during transportation. Exotic fragments include a quartz conglomerate fragment and a gabbro fragment that are 6 and 10 cm in diameter, respectively.

Channels are present in about 13% of the beds. These channels are U-shaped in profile and although most of them have steep sides, some are broad and shallow. Several channels may occur in the same horizon. Most channels are filled by granule-size greywacke. An exception is a 0.8 m deep channel north of Vermilion Lake; it is filled by steeply dipping crossbeds of brown, medium-grained calcareous sandstone.

Cantin and Walker (1972) described blunt-nosed flute casts. Groove marks occur locally. Features, resembling groove marks, may form at the contacts of beds of different competence and are due to deformation (Ramsay 1967).

Ripples and climbing ripples are common in division C (Photo 8.3).

Convolute laminations occur in 9% of the beds and vary in nature and scale. In Photo 8.5, the hammer lies on a bed containing small convolutes. The arcuate crack above the hammer head is the contact with the overlying bed which displays a large convolute. The convoluted part of this bed is 0.8 m thick, but the same bed, where convolutes are absent, is only 0.3 m thick. The above suggests slumping of the lower bed, deposition of the upper bed, followed by convolution of both beds. Locally, there are intervals which have a highly disrupted and chaotic appearance. These contain distorted fragments and convolutes, and are likely the product of submarine slides.

Load structures are produced by processes related to unequal loading and foundering and include flame and load casts (in 21% of the beds) and ball structures (in 2% of the beds). Flame structures are the result of the penetration of narrow pelitic dikes into the overlying beds. Some are up to 0.4 m high. Generally, pelitic material of division D penetrates division A of the overlying bed. Flame structures may be intricate in detail as some have their tops bent over and others have a mushroom-like appearance. A feature which resembles flame structures, but forms in a different way, is produced when the edge of a pelitic layer is partly ripped up by current action and later buried by sand. Load casts develop on the bedding plane and appear as broad depressions and sharp domes (Photo 8.6).

Unusual markings, possibly of biogenic origin, occur on local bedding planes. Some show branching arms with knobs near the end of some of the arms (Photo 8.7) and others display a pattern of fine lines



Photo 8.5. Hammer lies on a bed with small convolutes; the upper bed displays a large convolute. Vermilion River south of Highway 144.

(Rousell 1972, Plate 3, Figure 5). The former resemble the imprint of seaweed. Cantin and Walker (1972) suggest these markings are not imprints because they penetrate the bedding plane. Narrow vertical pipes, some looped, are common, and may be worm tubes.

Paleocurrents

Cantin and Walker (1972) determined paleocurrent directions from the orientation of flute casts, convolute laminations, channels, and ripple crests. The flute casts indicate a paleoflow direction to the southwest and parallel to the axis of the Sudbury Basin. The axes of the convolutes and channels also are oriented parallel to the axis of the basin. Ripple cross-laminations indicate no preferred paleoflow direction. These features may have formed by bottom currents unrelated to turbidity currents, or, as a result of random turbulence in the wake of turbidity currents. Rousell (1972) determined paleocurrent directions from cross-lamination, channels, lenticular beds, and current marks. The dominant current direction is southwest and parallel to the basin axis. There are several minor but divergent



Photo 8.6. Load casts. Highway 144 west of Vermilion River.

paleocurrent directions, notably south-southeast. Data from the most southwesterly locality indicate a northeast current direction.

Features such as the predominance of thick, coarse-grained layers of division A, channels, and the fact that virtually all beds begin with division A indicate that the beds of the Chelmsford Formation represent proximal turbidites. Cantin and Walker (1972) found no change in bed thickness from northeast to southwest along the axis of the Chelmsford outcrop belt. The unimodal paleocurrent direction and the lack of radially inward paleocurrents suggest that the Chelmsford Formation was deposited in an elongate trough. Turbidity currents probably travelled down the

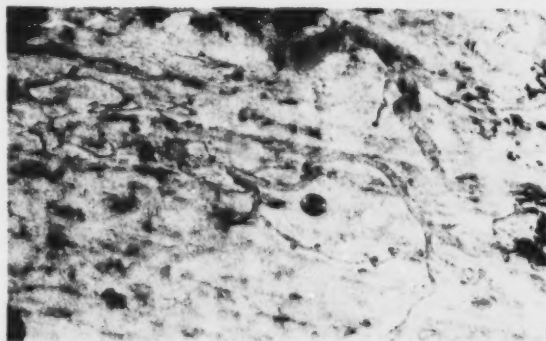


Photo 8.7. Possible biogenic structure. Abandoned section of Highway 144 north of the railroad overpass.

flanks of the trough, then turned and followed the southwesterly sloping axis (Cantin and Walker 1972).

DISCUSSION

French's (1967, 1972) model for the origin of the Sudbury Basin by meteorite impact involves the formation of a crater 100 km in diameter that contained a central uplift, followed by blanketing of the crater by fall-back breccia (Onaping Formation) and pelagic sediments (Onwatin Formation). According to this model, the central uplift later subsided, along steep faults, to form a depression; material from the margins of the depression and beyond were deposited in the depression to form the Chelmsford Formation. The model implies that the Onwatin and Onaping Formations supplied the material for the Chelmsford sediments.

The local slabs of argillite and siltstone in the Chelmsford Formation may have been derived from the Onwatin Formation. More likely, the slabs were derived from the Chelmsford Formation itself. Sediments of division D, deposited between turbidite flows, could have been reworked by subsequent flows. The bulk of the Chelmsford Formation consists of sandstone, whereas the Onwatin Formation consists largely of argillite and siltstone. The Onaping Formation contains abundant glass fragments and quartz and feldspar fragments, some of which display planar features attributed to shock metamorphism. Neither glass fragments nor planar features were observed in the Chelmsford Formation (Rousell 1972). The Chelmsford sediments do not appear to represent reworked material from the Onwatin and Onaping Formations (Williams 1957); the turbidites were apparently largely derived from a tonalite terrain such as that to the northwest of the basin (Rousell 1972).

The pelagic sediments of the Onwatin Formation and the turbidites of the Chelmsford Formation represent a progradational sequence. The deposition of this sequence may have been a response to the initial stages of the Penokean Orogeny. Uplift in a source area outside the basin supplied sand for the Chelmsford Formation. The presence of local greywacke beds and highly crenulated layers between undisturbed layers in the Onwatin Formation (Sadler 1958) suggest that orogenic activity may actually have begun during Onwatin deposition. Deformation compressed the original volcanic or meteoritic crater to form an elongate trough with a southwesterly plunging paleoslope. This slope was likely inherited from a regional paleoslope as paleocurrents in the Mississagi Formation, southeast of the basin, also flowed in a southwesterly direction (Long 1978). Turbidity currents, originating at the margins of the crater and directed radially inward, flowed down the flanks of the crater and on

CHAPTER 8

reaching the axis, turned and flowed to the southwest. Slabs of sedimentary material were locally torn off the crater margin and transported by turbidity currents toward the axis; unstable deposits on the flanks of the crater formed local submarine slides. The unimodal paleocurrent direction in the Chelmsford Formation and the fact that the formation was originally thicker and more extensive suggests that these rocks represent a preserved remnant of material deposited along the trough axis.

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CHAPTER 9

Mineralization in the Whitewater Group

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ABSTRACT

Mineralization in the Whitewater Group is as follows:

1. Disseminated sulphide minerals in the Onaping Formation. Pyrrhotite is the major sulphide mineral and occurs mainly as fragments; other sulphide minerals are chalcopyrite, pentlandite, sphalerite, galena, marcasite, and pyrite. The sulphide mineral content is variable, seldom exceeds 10%, and commonly is approximately 1% by volume.
2. Zn, Pb, Cu, Ag, and Au mineralization in the Vermilion Member, a carbonate-chert unit located near the base of the Onwatin Formation (Vermilion and Errington Mines).
3. Pyrite and local base metals in the Onwatin Formation. Pyrite occurs as silt-size grains arranged parallel to bedding planes and as lenses as thick as 20 cm. There are local moderately high Zn values.
4. Anthraxolite veins occur in the Onwatin Formation at 2 localities.
5. Mineralized quartz veins.

The Foisey Occurrence (Zn, Pb) and the Papi-neau Occurrence (Cu, Au, and Co) are located at the contact between the Sudbury Igneous Complex and the Onaping Formation. The Moore Lake Occurrence (Pb, Zn, and Ag) and the Proulx Occurrence (Pb, Zn,

and Cu) occur in the Basal Member of the Onaping Formation. Material from quartz veins from 2 former "gold mines" yielded no Au values. Quartz-carbonate veins in a metagabbro sill contain Cu, Zn, As, and Au.

The mineralization may be separated on the basis of time of formation. The fragmentary mineralization in the Onaping Formation formed during the initial Sudbury Event. According to the astrobleme theory, the transient crater penetrated to the upper mantle where sulphide-rich pods were present. The sulphide fragments were derived from the brecciation of these pods and from sulphide minerals in target rocks of the Huronian Supergroup. The Vermilion-Errington deposits and pyrite in the Onwatin Formation represent syngenetic sedimentary exhalative mineralization that formed during the deposition of the Onwatin Formation. Mineral-rich brines rose upward, deposited some Zn, Pb, and Cu as they passed through the Onaping Formation and on reaching the basin floor, precipitated the Vermilion Member under reducing conditions. These conditions persisted throughout the deposition of the upper Onwatin Formation, but pyrite was the only sulphide that formed. The anthraxolite veins and quartz veins were emplaced during a tectonometamorphic event. Metamorphism remobilized and concentrated carbonaceous material in the Onwatin Formation to form the anthraxolite veins. Quartz veins

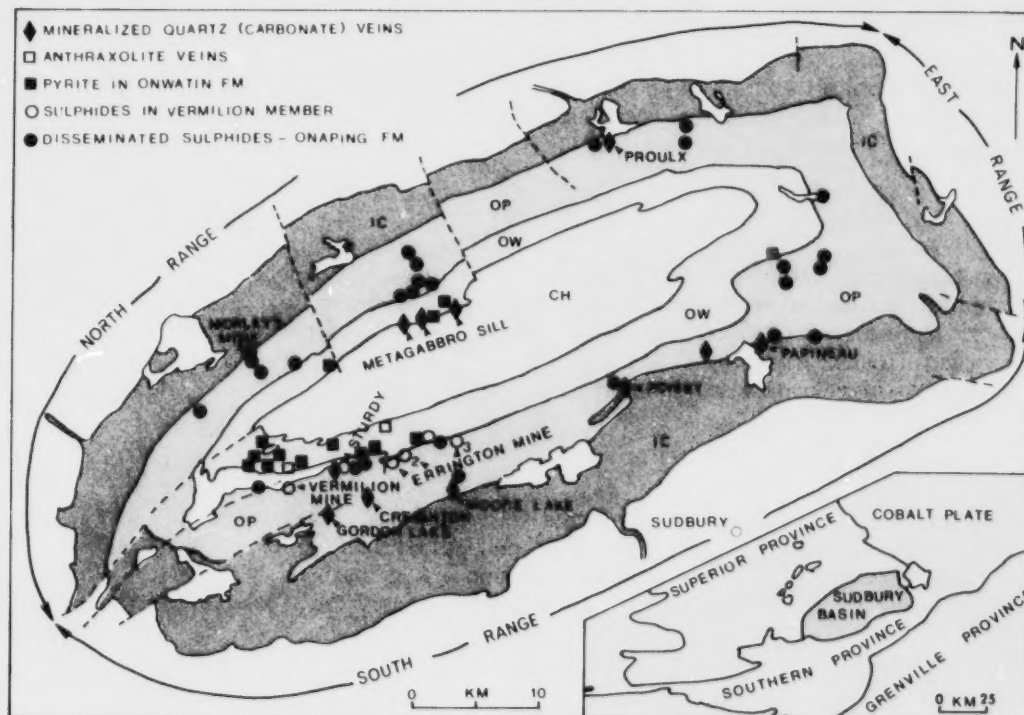


Figure 9.1. Geological map showing the location of mineral occurrences inside the Sudbury Basin. IC, Sudbury Igneous Complex; OP, Onaping Formation; OW, Onwatin Formation; and CH, Chelmsford Formation (after Rousell 1983).

are most common in the South Range where they are parallel to the tectonic foliation. The quartz-carbonate veins in the metagabbro sill are either syn- or are post-tectonic.

INTRODUCTION

The rocks of the Whitewater Group host a variety of mineral occurrences including 2 former base-metal mines. The mineralization may be grouped as follows: disseminated sulphide minerals in the Onaping Formation; sulphide minerals in the Vermilion Member of the Onwatin Formation; pyrite and local base metals in the Onwatin Formation; anthraxolite veins in the On-

watin Formation; and mineralized quartz veins. The location of these mineral occurrences are shown on Figure 9.1 and the mineralization is diagrammatically represented in the columnar section of Figure 9.2.

DISSEMINATED SULPHIDE MINERALS IN THE ONAPING FORMATION

Disseminated sulphide minerals are present throughout the entire Onaping Formation. The sulphide minerals occur mainly as discrete fragments, but there are also sulphide patches and grains within rock and glass fragments and in igneous-textured bodies that occur within the formation. The sulphide fragments, like the glass and rock fragments, are tectonically elongated in the South and East Ranges. Several of the occurrences are exposed in trenches and pits. One is exposed in an adit approximately 37 m in length (locally known as 'Morley's mine' - Figure 9.1). The sulphide content of these occurrences is variable. Muir (1980) and Lafleur (1981) noted that sulphide minerals in the North Range are most abundant in the upper part (Black Member) of the formation. The sulphide fragments are seldom more than 0.5 cm long; they rarely exceed 10%, and are commonly in the order of 1% by volume. Pyrrhotite is the major sulphide mineral and locally contains exsolved pentlandite. Desborough and Larson (1970) noted the local replacement of pyrrhotite by nickeliferous pyrite and nickeliferous marcasite. Chalcopyrite is common and is frequently enclosed by pyrrhotite, but, in general, composes less than 1% of the total sulphide minerals. Sphalerite, galena, marcasite, and pyrite occur in minor amounts.

Desborough and Larson (1970) determined the nickel content of pyrrhotite by electron microprobe analysis (8 grains in 3 specimens); the range is 0.1 to 0.35 wt%, and the average is 0.28 wt%. The ranges in the nickel content of pyrrhotite determined from 7 specimens selected from the Sudbury Igneous Complex (Duke and Naldrett 1976) and specimens from several Sudbury Ni-Cu mines (Hawley 1962) are 0.5 to 1.2 wt% and 0.76 to 2.65 wt%, respectively. The corresponding average nickel contents are 0.81 and 1.62 wt%, respectively. Thus, the nickel content of pyrrhotite is relatively low in the Onaping Formation, higher in the Sudbury Igneous Complex, and still higher in the Ni-Cu ores.

Trace element data from the Onaping Formation (Rousell 1982, 1983; Muir 1983; Arengi 1977; Sadler 1958) are summarized in Table 9.1 in terms of range and average values. Relatively high metal values are present in an exposure at the top of the formation, located immediately west of the Errington Number 2 shaft (Zn-2.32 wt%, Pb-6250 ppm, Ba-2839 ppm, and As-302 ppm), from an outcrop at the base of the

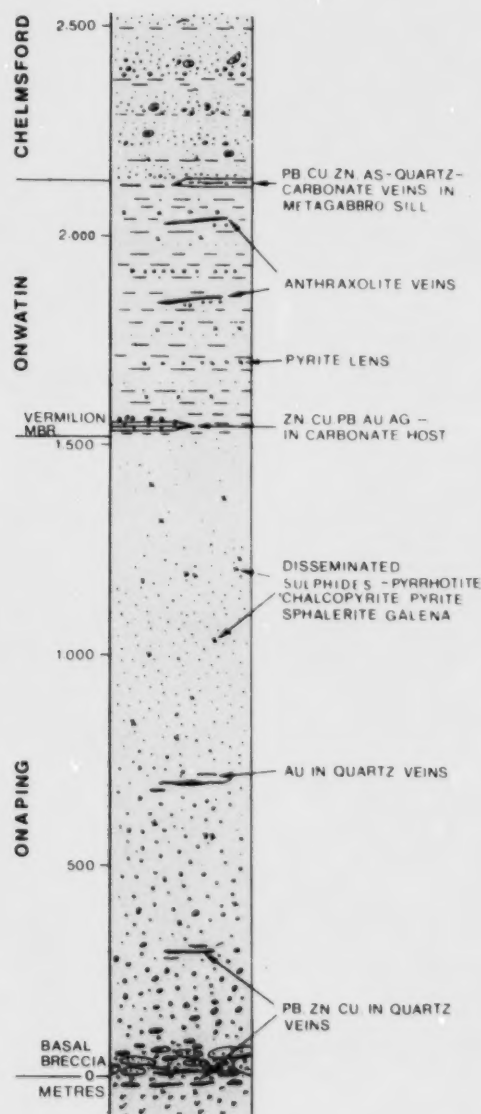


Figure 9.2. Diagrammatic representation of mineralization in the Whitewater Group (after Rousell 1983).

formation near the Foisey Occurrence (Zn-650 ppm, Pb-960 ppm, and As-152 ppm), from a diamond-drill hole between the Foisey Occurrence and the Papineau Occurrence (Zn-900 ppm), and from a drillhole between the Errington Number 3 shaft and the Foisey Occurrence (Cr-1440 ppm). Apart from these localities, metal values in the formation appear to be low to moderate.

The average abundance of certain elements in intermediate rocks (Krauskopf 1967) and basalt (Krauskopf 1979) are given in Table 9.1 for comparative purposes. It is difficult to compare the Onaping Formation with a particular rock type because of the heterogeneous nature of the unit (Peredery 1972; Muir 1982). Based on the chemical analyses of 6 selected

specimens, Stevenson (1972) concluded that the Onaping Formation ranges in composition from rhyodacite near the base to dacite toward the top. This corresponds most closely to the intermediate rock type (Krauskopf 1967). The rocks analyzed by Muir (1983) were classified as dacite, andesite, or basalt while those analyzed by Rousell (1982, 1983), Arengi (1977), and Sadler (1958) were not classified. The average metal values in the Onaping Formation are compared to the average values in intermediate rocks by a ratio of the 2 averages and to average metal values in basalt by a similar ratio (Table 9.1). For the analyses of Rousell (1982, 1983), the average used for Zn and Pb were obtained by omitting the maximum values. For intermediate rocks, the range in ratios are: Cu, 0.4 to 4.7; Zn, 1.5 to 5.6; Ni, 1.4 to 3.4; Co, 2.4 to 7; Pb, 1.1 to 4; Cr,

TABLE 9.1: SUMMARY OF TRACE ELEMENT CHEMICAL DATA FROM THE ONAPING FORMATION AND THE AVERAGE VALUE OF INTERMEDIATE ROCKS AND BASALT.

	ppm					ppb				
	Cu	Zn	Ni	Co	Pb	Ba	Cr	As	Ag	Au
Onaping Formation ²										
Range	15	ND	11	20	ND	41	9	ND	ND	ND
	325	2.32*	147	200	6250	2839	146	302	4.1	70
Average N = 28	85	955	48	47	272	553	80	28	0.3	
Average N = 27 ³		129			16					
Ratio ⁴	2.6	2	1.4	5.5	1.1		2.2	12.7	5	
Ratio ⁵	0.9	1.3	0.3	1	4.6	1.8	0.4	14	75	
Onaping Formation ⁶										
Range	5	130	27	13	< 10	250	88	—	—	< 2
	32	190	75	33	< 10	1550	168	—	—	20
Average N = 6	12	160	50	20	< 10	611	120			< 6
Ratio ⁴	0.4	2.4	1.4	2.4	< 1.5	—	3.3			< 1.5
Ratio ⁵	0.1	1.6	0.3	0.4	< 2.9	2	0.6			< 60
Onaping Formation ⁷										
Range	6	249	84	22	ND	240	205	—	ND	—
	103	900	211	121	45	2210	1440	—	17.1	—
Average N = 7	58	376	106	60	16	771	447		10	
Ratio ⁴	1.8	5.6	3	7	1.1		12.4		167	
Ratio ⁵	0.6	3.8	0.7	1.3	4.6	2.6	2.2		2500	
Onaping Formation ⁸										
Range	28	40	70	23	39	—	50	—	< 1	—
	282	160	155	43	83	—	86	—	42	—
Average N = 7	154	97	118	33	60		76		7	
Ratio ⁴	4.7	1.5	3.4	3.9	4		2.1		117	
Ratios ⁵	1.5	1.0	0.8	0.7	17		0.4			
Intermediate Rocks ⁹	32.5	66	35	8.5	15	—	36	2.2	0.06	4
Basalt ¹⁰	100	100	150	48	3.5	300	200	2	0.004	0.1

Notes:

- * = wt.%, ND = not detected, dash = not analyzed, and N = number of samples
- Rousell (1982, 1983)
- Average omitting 2.32 wt.% for Zn and 6250 ppm for Pb
- Ratio: average trace element value in Onaping Formation/average trace element value in intermediate rocks
- Ratio: average trace element value in Onaping Formation/average trace element value in basalt
- Muir (1983)
- Data from 2 drillholes located in the central part of the North Range (Arengi 1977)
- Data from 4 drillholes and 3 outcrops; 6 analyses from the northeastern part of the South Range and 1 from the East Range (Sadler 1958)
- Krauskopf (1967)
- Krauskopf (1979)

2.1 to 12.4; As, 12.7; and Ag, 5 to 167. Background metal values in the Onaping Formation are higher than values in intermediate rocks, particularly for Ag, As, and Cr. For basalt, the range in ratios are: Cu, 0.1 to 1.5; Zn, 1 to 3.8; Ni, 0.3 to 0.8; Co, 0.4 to 1.3; Pb, 2.9 to 17; Ba, 1.8 to 2.6; Cr, 0.4 to 2.2; As, 14; Ag, 75 to 2500; Au, < 60. Background metal values in the Onaping Formation tend to be higher than average values in basalt for Zn, Pb, Ba, As, Ag, and Au, and to be lower for Cu, Ni, Co, and Cr.

SULPHIDE MINERALS IN THE VERMILION MEMBER

The Vermilion Mine, the Sturdy Property, and the 3 shafts of the Errington Mine are located in the south-western corner of the basin (Figure 9.1). These Zn-Pb-Cu-Ag-Au deposits are in the Vermilion Member, a distinct carbonate-chert unit located near the base of the Onwatin Formation. The deposits occur over a length of 11 km and have an anomalously high magnetic signature (GSC 1960) that extends to the north-east and beyond the mines. The mines operated from 1926 to 1931, and from 1952 to 1956. The fine-grained nature of the ore caused problems in recovery. Giant Yellowknife Mines Limited, the present owners, completed a diamond-drilling program in 1979 at the Vermilion Mine in order to obtain fresh material for mill-testing purposes.

The Vermilion Member, from bottom to top, consists of carbonate rock, cherty carbonate rock, chert breccia, and interbedded argillite, limestone, and dolostone (see Figure 8.1). The rocks are folded and displaced by southeasterly-dipping reverse faults. Average ore grades are set out in Table 9.2. The sulphide minerals consist of pyrite, sphalerite, galena, chalcopyrite, marcasite, and pyrrhotite. There are 2 types of ore, disseminated ore and massive pyrite ore (Photo 9.1). The disseminated ore is fine grained and occurs in the carbonate rock. The massive ore is generally high in Zn and low in Cu. This ore occurs mainly at the base of the carbonate rock and replaces the underlying argillite. Quartz veins in the ore zone contain

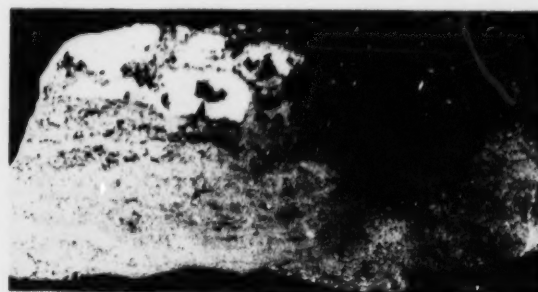


Photo 9.1. Massive pyrite ore from the dump at the Errington Number 2 shaft. Light grey carbonate rock (upper left) contains chalcopyrite blebs up to 1 cm in length. Bar is 3 cm.

TABLE 9.2: TRACE ELEMENT CHEMICAL DATA FROM THE VERMILION MEMBER

	Cu	Zn	Ni	Co	Pb	Ba	Cr	As	Ag	Au
	—wt. %—				wt. %				ppm	ppb
Errington Number 2 shaft ²	1.10	3.82			0.97				49.4	656
Errington Number 3 shaft ²	1.05	4.79			1.96				69.4	531
Vermilion Number 4 shaft ²	1.26	3.92			.97				43.8	781
Vermilion-north zone ²	0.34	3.73			1.30				51.3	625
Average	0.94	4.07			1.30				53.5	648
Low pyrite ore ³	1.33	3.97			1.0				50.3	813
High pyrite ore ⁴	1.14	3.82			0.99				49.4	719
	ppm									ppb
Outcrop, W82 ⁵	120	9000	10	20	175	25	ND	77	—	—
Outcrop, W81-1 ⁶	70	45	ND	40	ND	ND	0.6	27	—	—
Outcrop, W81-2 ⁶	9000	3.8*	20	60	1.6*	ND	4	7800	—	—
Outcrop, W81-3 ⁶	2000	4.1*	100	35	8000	460	30	1100	—	—
DDH's ⁸	34	390	62	30	111	248	70	—	11	—
Errington Number 3 dump, W88 ⁷	1300	3.0*	28	14	525	45	26	42	4	30
Vermilion Mine dump ⁸	1.03*	3.45*	62	193	1.43*	215	68	—	71	—

Notes:

1. * = wt.%, ND = not detected, and dash = not analyzed
2. Average values of ore (Thomson 1957)
3. Average of 4 418 500 tons (Canadian Mines Handbook 1964)
4. Average of 9 038 317 tons (Canadian Mines Handbook 1964)
5. W82—between Errington Number 2 and Number 3, W81—at Errington Number 1 (Rousell 1983)
6. Average of 4 samples from 2 diamond-drill holes in the central part of the South Range (Arenghi 1977)
7. (Rousell 1983)
8. Average of 4 samples (Arenghi 1977)

coarse-grained sphalerite, galena, and chalcopyrite, whereas quartz veins outside the ore zone are barren.

According to Burrows and Rickaby (1930), ore was exposed at 5 localities in the vicinity of the mines; only 2 of these are presently exposed. One, located between Errington Number 2 and Number 3 shafts, consists of a lenticular gossan 2 m wide enclosed by argillite and siltstone of the Onwatin Formation. The gossan consists mainly of mottled grey and white dolomite as well as minor amounts of quartz and sulphide minerals. A chemical analysis of this material (W82, Table 9.2) gave a Zn content of 0.9 wt%. The Vermilion Member is well exposed at the northwestern edge of a ridge occupied by the Errington Number 1 shaft (Photo 9.2). There, chert breccia consists of black, chip-like fragments of chert, as much as 5 cm in length, set in a matrix of white, very fine grained quartzite; the rock is not mineralized (W81-1, Table 9.2). A dense, fine-grained siliceous rock is associated with the chert breccia. Most of the exposure consists of a medium- to coarse-grained, massive, dolomitic rock containing abundant sulphide minerals including sphalerite, pyrite, galena, and chalcopyrite. Chemical analyses of the material (W81-2, W81-3, Table 9.2) returned an average Zn content of 3.9 wt% together with Pb, Cu, and As values.

Rocks of the Vermilion Member have been penetrated by several drillholes in the North and South Ranges. Average metal values for 4 specimens from 2 drillholes in the South Range are given in Table 9.2, and indicate low metal values (Arengi 1977).

PYRITE AND METALS IN THE ONWATIN FORMATION

The Onwatin Formation is rich in pyrite. This pyrite occurs as abundant silt-size grains arranged parallel to

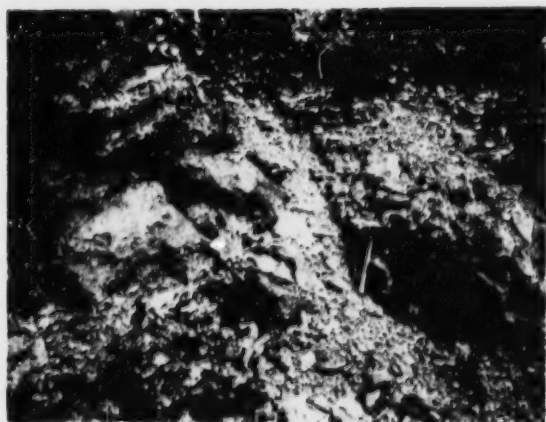


Photo 9.2. Outcrop of the Vermilion Member at Errington Number 1 shaft.



Photo 9.3. Pyrite lenses and slaty cleavage in the Onwatin Formation. Vermilion Lake Road.

the bedding plane and as massive lenses (Photo 9.3), generally 1 to 3 cm thick, but locally as thick as 20 cm. The presence of pyrite along cleavage planes indicates remobilization. Pyrite cubes, as much as 2 cm in diameter, form nodular masses and are the result of recrystallization.

Trace element chemical data from the Onwatin Formation are summarized in Table 9.3 in terms of range and average values. The data for the Onaping-Onwatin transition zone and the basal argillite of the Onwatin Formation (Sadler 1958) indicate only moderate trace element values. The analyses by Rousell (1982, 1983) are for specimens taken from outcrops; all, except one, are from the western part of the basin. Apart from a moderate Zn value (1250 ppm) in an exposure between Errington Number 2 and Number 3 shafts, none of the specimens contain a high metal content. The data of Sadler (1958) and Arengi (1971) indicated moderately high Zn and Cu values.

Average metal values in shale (Krauskopf 1979) are given in Table 9.3. Average trace element values in the Onwatin Formation may be compared with those in shale by a ratio of the 2 averages (Table 9.3). The Onaping-Onwatin transition zone and basal argillite of the Onwatin Formation (Sadler 1958) contain very high background values of Ag and Cu and high background values of Co and Pb; Zn, Ni, and Cr values are also in excess of those in shale. The analyses by Rousell (1982, 1983) indicated moderately high background values of As, Ag, Co, and Ba. The data of Sadler (1958) show very high background values of Ag

TABLE 9.3: SUMMARY OF TRACE ELEMENT CHEMICAL DATA FROM THE ONWATIN FORMATION AND THE AVERAGE VALUE IN SHALE.

	ppm								ppb	
	Cu	Zn	Ni	Co	Pb	Ba	Cr	As	Ag	Au
Transition ²										
Range	245	53	120	38	50	—	80	—	< 1	
Average N = 11	600	418	350	144	110	—	282	—	11	
Ratio ⁶	394	163	223	70	70		134		< 4	
Ratio ⁶	7.9	1.8	2.8	3.5	3.5		1.3		~ 40	
Onwatin Formation ³										
Range	ND	10	26	ND	ND	287	46	ND	ND	ND
Average N = 11	105	1250	155	125	120	4828	128	162	0.6	10
Ratio ⁶	49	155	63	50	22	1465	94	37	0.33	—
Ratio ⁶	1	1.7	0.8	2.5	1.1	2.5	.9	3.7	3.3	
Onwatin Formation ⁴										
Range	15	51	46	11	18	—	72	—	< 1	
Average N = 11	600	5610	271	165	135	—	167	—	7.5	—
Ratio ⁶	168	1320	144	55	62		129		< 2	
Ratio ⁶	3.4	14.7	1.8	2.8	3.1		1.3		~ 20	
Onwatin Formation ⁵										
Range	11	326	59	24	ND	250	136	—	ND	
Average N = 6	724	7420	244	81	150	1340	307	—	25	
Ratio ⁶	230	1917	133	49	53	778	225		17	
Ratio ⁶	4.6	21.3	1.7	2.5	2.7	1.3	2.3		170	
Shale ⁷	50	90	80	20	20	600	100	10	0.1	3

Notes:

1. * = wt.%, ND = not detected, dash = not analyzed, and N = number of samples
2. Onaping-Onwatin transition zone and basal argillite of Onwatin Fm; data from 3 diamond-drill holes located in northeastern part of the South Range (Sadler 1958)
3. Data from outcrops (Rousell 1982, 1983)
4. Data from several diamond-drill holes and outcrops in North and South Ranges (Sadler 1958)
5. Data from 2 diamond-drill holes located in the central part of the North Range and 1 from a diamond-drill hole located in the central part of the South Range (Arengi 1977)
6. Ratio: average trace element value in Onwatin Formation/average trace element value in shale.
7. Average trace element content (Krauskopf 1979)

and Zn and moderately high background values of Cu, Co, and Pb; and that of Arengi (1977) show extremely high background values of Ag, very high values of Zn, and moderately high values of Cu, Co, Pb, and Cr compared to average values in shale.

In summary, average metal values in the Onwatin Formation exceed average metal values in shale. Background values of Ag, Zn, and Cu are particularly high in the formation. Most of the material analyzed by Sadler (1958) and Arengi (1977) came from drillholes and yielded higher metal values than outcrop material analyzed by Rousell (1982, 1983). The drillholes apparently intersected relatively mineral-rich zones.

ANTHRAXOLITE VEINS

Two anthraxolite veins occur in the Onwatin Formation. One is located north of the Errington Number 1 shaft and the other is north of the Vermilion Mine. The anthraxolite is a black, dense, platy material that contains quartz and pyrite and consists of approximately 95% carbon. The vein north of the Errington Number 1 shaft is exposed in a 30 m long inclined adit and in 2 smaller adits. There was considerable local interest in

the vein before the turn of the century as it was thought that the material could be used as a fuel (Burrows and Rickaby 1930). However, it proved unsuitable due to the high ash content.

QUARTZ VEINS

Sulphide-bearing quartz veins occur at the contact of the Sudbury Igneous Complex and the Onaping Formation (Foisey and Papineau Occurrences, see Figure 9.1) and in the Basal member of the Onaping Formation (Moore Lake and Proulx Occurrences and Morley's Mine, see Figure 9.1). Quartz veins, supposedly gold-bearing, are present in the lower part of the Onaping Formation (Gordon Lake Mine, Creighton Gold Mine). A metagabbro sill, located at the contact between the Onwatin and Chelmsford Formations, hosts mineralized quartz-carbonate veins. Quartz veins are common in the South Range, but they are relatively scarce in the North Range. T.L. Muir (Geologist, Ontario Geological Survey, personal communication, 1983) noted quartz veins that contained minor pyrrhotite and pyrite in Norman Township in the East Range. Trace element chemical analyses of specimens from

TABLE 9.4: TRACE ELEMENT CHEMICAL DATA FROM QUARTZ VEINS AND HOST ROCKS².

Specimen Number	ppm									ppb Au
	Cu	Zn	Ni	Co	Pb	Ba	Cr	As	Ag	
W3-1A Foisey	160	8.5*	22	200	6750	464	59	1400	7.6	60
W3-2 Foisey, HR	10	130	25	80	45	637	34	22	ND	ND
W10-A Papineau	5000	1	6	160	25	77	18	1.3*	2	869
W10-B Papineau	3000	1	40	580	80	125	29	10.1*	3	2400
W11 Papineau	150	ND	10	305	3	1477	4	45	< 1	820
W35-1 metagabbro sill, HR	55	165	22	70	115	440	25	38	1.4	ND
W36-1 metagabbro sill	60	10	40	230	ND	46	31	18.6*	7	1610
W37 metagabbro sill	1.0*	2500	40	280	420	1	17	ND	2	ND
W39-1 metagabbro sill	3	5	10	165	ND	6	16	4400	ND	10
W39-2 metagabbro sill, HR	2	55	50	37	5	341	22	109	0.6	30
W65 metagabbro sill	135	50	25	40	ND	62	10	28	1	ND
W44-1 Gordon Lake	ND	25	15	87	310	221	17	ND	1	ND
W44-2 Gordon Lake	ND	ND	32	155	ND	21	12	35	ND	ND
W44-3 Gordon Lake, HR	2	5	55	45	2	739	131	10	ND	ND
W52-1 Moore Lake, HR	45	50	25	200	15	83	52	900	ND	ND
W52-2 Moore Lake	50	1.93*	56	160	2.73*	70	37	4.5*	264	ND
W60 Creighton	20	150	132	120	10	1546	492	82	ND	ND
W61-1 Creighton, HR	160	10	36	62	15	213	96	1J	ND	ND
W61-2 Creighton	5	3	22	215	ND	59	15	1	ND	ND
W61-3 Creighton	40	7	38	133	11	662	18	24	ND	ND
W61-4 Creighton	40	95	54	68	15	19	9	ND	ND	ND

Notes:

1. * = wt.%, ND = not detected, and HR = host rock

2. Rousell (1982, 1983)

veins and host rocks (Rousell 1982, 1983) are set out in Table 9.4.

Sulphide-Bearing Quartz Veins

The most mineralized quartz vein at the Foisey Occurrence is approximately 1 m thick and is within an igneous-textured rock that forms the matrix of the Basal Member of the Onaping Formation at this locality. Sphalerite, galena, and chalcopryrite compose approximately 90%, 9%, and 1% by volume of the sulphide minerals, respectively. A chemical analysis of a specimen of the vein (W3-1A) indicates high values of Zn and Pb and minor amounts of Ag and Au. An analysis of the host rock (W3-2) indicates a low metal content.

Quartz veins and blebs, as much as 5 m thick, are very numerous at the Papineau Occurrence. These are within an igneous rock (granophyre?) that is stratigraphically below the Basal Member of the Onaping Formation. At the Papineau shaft, a 2.5 m thick quartz vein contains massive arsenopyrite and some pyrite and mauve-coloured carbonate material. The carbonate contains chalcopryrite, malachite, and azurite. Chemical analyses of 2 specimens from the vein (W10-A, W10-B) indicate relatively high As and Cu values, moderately high Au and Co values, and a trace of Ag. A vein occurring a few 10s of m north of the shaft locally contains arsenopyrite; a chemical analysis of a specimen from the vein (W11) shows relatively high Au, Co, and Ba values.

The Moore Lake Occurrence consists of several quartz veins, each approximately 10 cm thick, within

the Basal Member of the Onaping Formation. Galena occurs in masses as much as 5 cm wide together with sphalerite, pyrite, and minor chalcopryrite. A chemical analysis of a specimen from a vein (W52-2) shows a high Pb and Zn content and some Ag. The host rock contains considerable pyrite, but a chemical analysis (W52-1) indicates low trace element values.

Burrows and Rickaby (1930) briefly described the Proulx Occurrence. A shaft was sunk to a depth of at least 20 m within the basal member of the Onaping Formation where 2 quartz veins, 1.5 and 2.4 m thick, contain appreciable amounts of sphalerite, galena, and chalcopryrite. The shaft and veins are no longer exposed.

Lafleur (1981) and Lafleur *et al.* (1982) reported the presence of north to northwesterly-trending shear zones in the Onaping Formation in Dowling Township. Some shears extend more than 20 m along strike and contain galena, sphalerite, chalcopryrite, and pyrite. Quartz veins in Morley's Mine have up to 8.88% Zn, 11.8% Pb, and 0.42% Cu (Lafleur 1981).

Gold-Bearing Quartz Veins

The Gordon Lake and Creighton "Gold Mines", abandoned around the turn of the century, are described by Blue (1894).

The Gordon Lake Property is located in lot 2, concession IV, Fairbank Township. The site is presumably a prominent outcrop of quartz-rich rock on the western side of the Gordon Lake Road.

The quartz-rich rock occurs within the Onaping Formation, is 12 m thick, dips steeply to the southeast, contains numerous quartz veins and blebs, and is internally folded. The rock is pale pink and medium grained, consists of strained quartz grains that are locally highly fractured, together with some plagioclase grains in a fine-grained matrix of recrystallized quartz. Pyrite and limonite are abundant. The quartz-rich rock may represent a quartzite fragment from a Basal Member of the Onaping Formation that has been emplaced in its present position by faulting. A light green rock consisting of carbonate, quartz, and chlorite occurs beneath the quartz-rich rock.

Chemical analyses of 2 specimens of the quartz-rich rock (W44-1, W44-2) and 1 specimen of the green rock (W44-3) revealed no gold, nor significant amounts of any other metal.

The Creighton Gold Mine is located in lot 11, concession V, Creighton Township. During the time of operation, gold values were between \$4 and \$20 per ton of ore (Blue 1894); in 1893, the price of gold was \$20 per ounce.

An abandoned shaft is located on the property, and there is a large dump on it. Quartz veins extend over a width of 12 m and can be traced 100 m along strike until they disappear under a swamp. The quartz veins and surrounding rocks of the Onaping Formation contain minor disseminated sulphide minerals. Chemical analyses of 3 specimens (*see* Table 9.4) from the quartz veins (W61-2, W61-3, W61-4) and of a specimen of the country rock (W61-1) failed to detect gold; values of other metals are also low. Similar results were obtained from a specimen from a quartz vein near the Creighton Mine (W60).

Sulphide-Bearing Quartz-Carbonate Veins in a Metagabbro Sill

A metagabbro sill, as much as 30 m thick, is exposed at 3 localities over a length of 4 km and occurs at the contact between the Onwatin Formation and the Chelmsford Formation in northern Balfour Township. The rocks are altered, but primarily, pyroxene is locally preserved. The sill is the locus of mineralized quartz-carbonate veins and blebs that have been explored by numerous trenches and pits. The veins and blebs, up to 1.7 m thick, are commonly intimately mixed with the metagabbro. The carbonate is buff-coloured, weathers to a chocolate brown, and is probably ankerite or siderite. Pyrite, commonly cubic, locally weathers to limonite and hematite, arsenopyrite is prominent, and occurs as lenses and veinlets a few cm across. Chalcopyrite is locally present and alters to malachite.

Table 9.4 sets out trace element analyses of 4 specimens of quartz-carbonate material and 2 speci-

mens of the metagabbro. Specimen W36-1 is from a vein with massive arsenopyrite, and it contains appreciable Au and Ag. Specimen W37 is from a vein with visible chalcopyrite and has high Cu and Zn values and a modest Pb content. Specimens W39-1 and W65 apparently represent material from barren veins, but W39-1 has a moderately high As content. Both specimens of the metagabbro (W35-1, W39-2) contain disseminated pyrite, but neither has significant metal values; W39-2 contains traces of Au.

ORIGIN OF MINERALIZATION

The mineralization inside the basin may be separated on the basis of time of formation as follows (Rousell 1983):

1. fragmentary mineralization derived from pre-existing sulphides as a result of the initial Sudbury Event (sulphide fragments in the Onaping Formation)
2. mineralization that formed after the deposition of the Onaping Formation and before the deposition of the Chelmsford Formation (Vermilion-Errington deposits, pyrite in Onwatin Formation)
3. mineralization formed during a tectonic event (anthraxolite veins, quartz veins).

Sulphide Minerals in the Onaping Formation

The presence of sulphide minerals in the Onaping Formation, mainly as pyrrhotite fragments, suggests that sulphide-rich material must have been present prior to brecciation and incorporation into the unit. Sulphide fragments occur in felsic pyroclastic rocks associated with Precambrian massive sulphide deposits, and the fragments may have been derived from original sulphide layers by slumping or explosive volcanism (Sangster and Scott 1976).

The Onaping Formation is considered by some (Thomson 1957; Williams 1957; Stevenson 1972; Card and Hutchinson 1972) to consist largely or wholly of pyroclastic rocks, and it could be argued that the sulphide fragments were formed from pre-existing sulphide layers by volcanic processes.

Investigators including Dietz (1972), Guy-Bray (1972), and Pattison (1979) proposed that the Ni-Cu ores of the basin formed as a result of meteorite impact. Figure 9.3 is a diagrammatic representation of the evolution of the basin according to this theory. Figure 9.3A shows the target area just prior to impact. The outline of the maximum transient crater is indicated and it supposedly penetrated as deep as the upper mantle where sulphide-rich pods were presumably present. According to this theory (Pattison 1979), the sulphide-rich pods, together with silicate rocks,

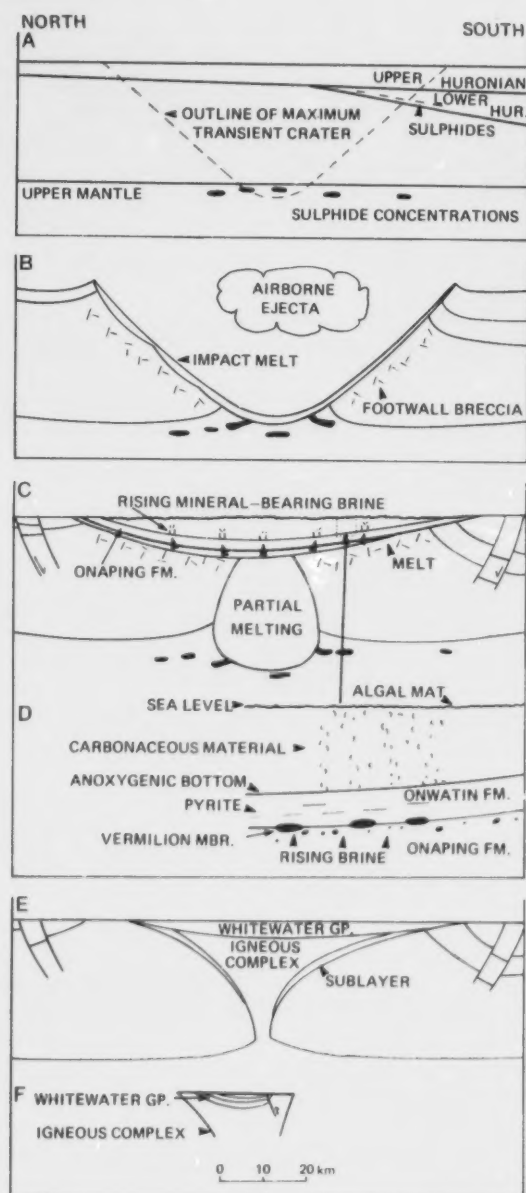


Figure 9.3. Schematic representation of the evolution of the Sudbury Basin by meteorite impact (after Dence 1972; Pattison 1979) and the origin of mineral occurrences inside the basin (from Rousell 1983).

formed an impact melt that travelled up the crater wall (Figure 9.3B); the sulphide minerals separated from the melt due to density differences and produced the Ni-Cu ore bodies in the Sublayer (Figure 9.3E).

Metasedimentary and tuffaceous rocks of the Elsie Mountain and Stobie Formations (Huronian Supergroup) are exposed to the south of the basin where locally they contain as much as 10% sulphide minerals (Figure 9.3A). These sulphide minerals are mainly pyrrhotite together with some pyrite and chalcopyrite (Innes 1972).

Some of the sulphide material in the pods and in the Huronian rocks may have been brecciated by meteorite impact and together with the silicate material, were incorporated in the airborne ejecta. This material, presumably in a molten or semi-molten state (Peredery 1972), fell back into the crater to form the Onaping Formation and the enclosed disseminated sulphide fragments.

Vermilion-Errington Deposits and Mineralization in the Onwatin Formation

The Vermilion-Errington deposits were originally thought to represent irregular pods scattered throughout masses of carbonate-chert rock. The presence of faults suggested a genetic connection between faulting and sulphide minerals. The mineralization was interpreted in terms of the classical hydrothermal concept; that is, the sulphide minerals were supposedly derived from mineral-bearing solutions emanating from the Sudbury Igneous Complex. These solutions were at lower temperatures than the solutions, also derived from the Complex, that produced the Ni-Cu ores (Burrows and Rickaby 1930).

Further studies, after the reopening of the mines in 1952, indicated that the deposits were stratigraphically and structurally controlled. Thomson (1957) suggested that the host rocks may be sedimentary in origin, that the chert breccia might be the result of slumping or later deformation, and that these brecciated horizons were amenable to mineralization. According to Martin (1957), the ore occurs mainly on the southern limb of folds and the limbs are the site of thrust faults. The faulting led to brecciation of the Vermilion Member and prepared the rocks for epigenetic mineralization. Martin (1957) further stated that some or most of the chert, carbonate, and pyrite might be the result of hot-spring activity that occurred during the last phase of Onaping volcanism.

Card and Hutchinson (1972) elaborated on these earlier concepts and considered the deposits in terms of regional volcanic-tectonic cycles. These authors regarded the Onaping Formation to be a product of explosive volcanism during a second cycle. During the later phases of this cycle, 2 metal- and sulphur-rich phases supposedly formed: a melt which differentiated at depth to form the Sudbury Igneous Complex and the Ni-Cu ores outside the basin, and a volatile phase which escaped to the surface to form the Vermilion-Errington deposits inside the basin.

Arengi (1977) assumed that the basin was formed by meteorite impact and suggested that the upper surface of the Onaping Formation (fall back breccia) was flat. Disruption of the surface, possibly due to the emplacement of the Sudbury Igneous Complex, gave rise to local highs on which carbonate banks developed

(Vermilion Member); basal argillites and siltstones of the Onwatin Formation were deposited between the banks.

Sangster (1970) divided Canadian stratabound Pb-Zn deposits into 2 types: the Mississippi Valley type and the Remac type (after the Reeves-MacDonald Mine, Kootenay Arc structural province, British Columbia; later referred to as Alpine type (Sangster and Scott 1976). The former deposits occur in relatively undeformed platform carbonates and are located between or at the margins of basins. The ores are younger than the host carbonate and were emplaced in permeable zones formed by processes such as brecciation, fracturing, and dolomitization. The rocks of the Remac deposits are highly deformed; the ore is fine to medium grained and is banded. The carbonate host is composed of alternating light bands and dark graphite-bearing bands of dolomite. In general, the stratigraphic succession for Kootenay Arc Pb-Zn deposits from bottom to top, is; quartzite, thin-bedded limestone and dolomite, local chert, and black carbonaceous shales (Høy 1982). The succession suggests the rocks were deposited in the centre of a basin and in a deep-water euxinic environment rich in H_2S ; metal-bearing solutions precipitated sulphide minerals as a layer on the seafloor, syngenetic with the host rocks (Sangster 1970.)

The stratigraphic succession associated with the Vermilion-Errington deposits, namely basalt argillite, banded carbonate with mineral layers, chert, and black carbonaceous pyritic shale (Onwatin Formation), suggests these deposits are similar to the Remac type. The basal argillite, interpreted by Martin (1957) to be a volcanic mud leached by hot acids, may represent an alteration halo. The Vermilion-Errington deposits may be sedimentary-exhalative deposits as described by Carne and Cathro (1982), and the 'volatile phase' of Card and Hutchinson (1972) might actually represent metal-rich brines. The process could have been triggered by meteorite impact.

A model for the formation of these deposits follows. The impact site was a shallow sea and some seawater penetrated to the bottom of the deep transient crater and became trapped by the fall back breccia. The crater then filled with seawater, possibly by means of a tsunami-like wave (Peredery 1972), and the outer rim gave rise to a closed basin much larger than the present remnant basin (compare Figures 9.3C and 9.3F). The abundant carbonaceous material, perhaps derived from floating algal mats or washed into the basin by the tsunami-like wave (Peredery 1972), suggests that bottom waters were stagnant and anoxic (Figure 9.3D). The trapped brines, possibly augmented by a 'volatile phase' formed as a result of pressure-release due to impact, rose upward, deposited some Zn, Pb, and Cu as they passed through the Onaping Formation and on reaching the basin floor, precipitated the Vermilion Member. Deposition could have been about lo-

cal vents, or, if the Onaping Formation was more-or-less uniformly porous, in depressions on the depositional surface. Minor amounts of metals were precipitated between the vents or depressions in the basal argillites and siltstones of the Onwatin Formation. Reducing conditions apparently prevailed throughout the deposition of the Upper Onwatin Formation, but pyrite was the only sulphide that formed.

Further evidence of the origin of the Vermilion-Errington deposits may be obtained by comparing them to other sediment-hosted Cu-Pb-Zn deposits. Figure 9.4 is a plot of Cu-Pb-Zn ratios of a number of such deposits (after Gustafson and Williams 1981). The symbols refer to the lithology of the host rocks and the deposits are listed in Table 9.5. The Vermilion-Errington deposits are indicated as B to E (see Table 9.2 for data) with the ratio of the average plotted at F (Zn = 64.5%, Pb = 20.6%, and Cu = 14.9%). The solid line encloses the field (lower right) of North American Precambrian massive sulphide deposits and the broken line encloses the field (lower right) of Canadian and Japanese Phanerozoic massive sulphide deposits; both are in volcanic or volcano-sedimentary host rocks (after Sangster and Scott 1976). The Mississippi Valley-type carbonate-hosted deposits tend to be relatively rich in Pb, or Pb and Zn, and lack Cu. The Alpine-type carbonate deposits are either relatively

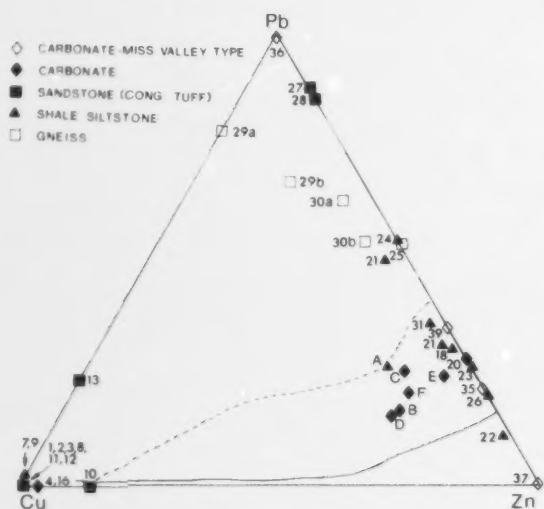


Figure 9.4. Cu-Pb-Zn ratios of sediment-hosted stratiform deposits. Host rocks are indicated by symbols. Data for the Errington and Vermilion Mines (Table 9.2) are from Thomson (1957) and that for Mississippi Valley type deposits are from Sangster (1976). Solid line—field (lower right) of North American Precambrian massive sulphide deposits in volcanic or volcano-sedimentary host rocks; and broken line-field (lower right) of Canadian and Japanese Phanerozoic massive sulphide deposits in volcanic or volcano-sedimentary host rocks (Sangster and Scott 1976). The rest of the data are from Gustafson and Williams (1981); names of the deposits are listed in Table 9.5 with the numbers identical to those used by these authors (after Rousell 1983).

TABLE 9.5: LIST OF ORE DEPOSITS PLOTTED ON FIGURE 9.4.

1. Mufulira, Zambia	26. Howard's Pass, Canada
2. Rokana, Zambia	27. Laisvall, Sweden
3. Chibuluma, Zambia	28. Largentière, France
4. Shaba, Zaire	29a. Aggeneys (Black Mountain, open pit) South Africa
6. Redstone River, Canada	29b. Aggeneys (Black Mountain, underground) South Africa
7. White Pine, USA	30a. Aggeneys (Broken Hill, open pit) S.A.
8. Spar Lake, USA	30b. Aggeneys (Broken Hill, underground) S.A.
9. Creta, USA	31. Faro, Canada
10. Boleo, USA	32. Vangorda, Canada
11. Corocoro, Mexico	33. Gortdrum, Ireland
12. Nacimiento, USA	34. Mallow, Ireland
13. Dzhezkazgan, USSR	35. Tri State, USA
15. Lubin, Poland	36. Old Lead, USA
16. Mt. Isa (Cu), Australia	37. Upper Mississippi Valley, USA
17. Mt. Isa (Pb-Zn), Australia	38. Upper Silesia, Poland
18. McArthur River (H.Y.C.), Australia	39. Pine Point, Canada
19. Tynagh, Ireland	A. Kupferschiefer regional ratio
20. Silvermines, Ireland	B. Errington Number 2
21. Rammelsberg, Germany	C. Errington Number 3
22. Meggen, Germany	D. Vermilion Number 4
23. Lady Loretta, Australia	E. Vermilion north zone
24. Sullivan, Canada	F. Average of B, C, D, and E
25. Broken Hill, Australia	

Cu-rich or Pb-Zn rich. The sandstone-hosted deposits are either rich in Cu with minor amounts of Pb or Zn, or are Pb-rich with minor Zn. Shale-hosted deposits are Cu-rich or contain Pb and Zn with minor Cu. Deposits in gneiss contain mainly Pb with variable amounts of Cu and Zn. The Vermilion-Errington deposits, Precambrian in age, fall outside of the field of North American Precambrian massive sulphide deposits. The latter deposits are notably deficient in Pb (Sangster 1972), whereas the Vermilion-Errington deposits contain appreciable lead. This suggests that the Vermilion-Errington deposits are not related to volcanic processes. S.N. Charteris (as of November 1, 1983, Staff Geologist, Corporation Falconbridge Copper, written communication, 1983) pointed out that some Archean volcanogenic deposits such as Sturgeon Lake Mines (1.47% Pb) and Matabi Mines Limited (1.06% Pb) are not Pb deficient; thus, the presence of Pb in the Vermilion and Errington deposits may not exclude them from being related to volcanic processes. Figure 9.4 also illustrates the separation between Pb-Zn deposits and Cu deposits. Note that the Vermilion-Errington deposits contain nearly as much Cu as Pb.

Mineralization and Basin Deformation

Rocks of the Onaping Formation in the South Range are characterized by a tectonic foliation and numerous quartz veins, whereas those of the North Range are undeformed and quartz veins are scarce. The strike of the quartz veins in the South Range is parallel to the strike of the tectonic foliation; the veins are not geometrically related to a prominent northwesterly-trending joint set (Rousell and Everitt 1981). Accordingly,

the veins were apparently emplaced at the time of the major deformation.

The exact time of emplacement of the mineralized metagabbro sill and the enclosed quartz-carbonate veins is not known. A similar metagabbro sill occurs in the Onwatin Formation north of Vermilion Lake (Burrows and Rickaby 1930). Cleavage in the Onwatin Formation passes into sill rocks, suggesting this sill was emplaced before or during basin deformation.

Tectonometamorphism remobilized and concentrated carbonaceous material in the Onwatin Formation to form the anthraxolite veins, folded and faulted the Vermilion-Errington deposits, elongated the sulphide and other fragments in the Onaping Formation, and locally remobilized and recrystallized material in the Onwatin Formation.

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GEOLOGY OF THE SUDBURY IGNEOUS COMPLEX

Introduction to the Geology of the Sudbury Igneous Complex

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The Sudbury Igneous Complex consists of a variety of igneous units intruded along the contact between the overlying Onaping Formation and the Levack Gneiss Complex on the North Range of the Sudbury Basin, and between the Onaping Formation and various formations and intrusions of the Southern Province along the South Range.

The lowermost unit of the Complex is the Sublayer. This unit consists of a range of noritic, gabbroic, and quartz dioritic rocks occupying radial and concentric fractures peripheral to the Sudbury Basin, and also occurring discontinuously along the lower contact. The Sublayer occupying the fractures tends to be richer in quartz and amphibole than that along the contact, has a quartz dioritic as opposed to a noritic or gabbroic composition, and is described in Chapter 12 by Grant and Bite (this volume). That occurring marginal to the Complex is described by Naldrett *et al.* (Chapter 11, this volume).

The various units of the Lower Zone occur more continuously around the structure. These units include the Quartz-rich Norite, which forms the marginal zone along the South Range and which grades upward into the South Range Norite. On the North Range, the Mafic Norite occurs discontinuously and is overlain

abruptly, but without chilled contacts, by the Felsic Norite. The uppermost part of the South Range Norite is equivalent petrographically to the Felsic Norite of the North Range.

The Middle Zone consists of a single unit, the Quartz Gabbro, which occurs all around the Complex. The base of the unit is marked by the incoming of cumulus Fe-Ti oxides, titaniferous magnetite on the North Range, and magnetite and ilmenite on the South Range. A gradational increase in the proportion of a granophyric intergrowth of quartz, plagioclase, and potassic feldspar within the upper part of the Quartz Gabbro marks its transition into the Granophyre of the Upper Zone.

The Granophyre usually contains 75 to 80% of the intergrowth, although a content of 50 modal % is usually taken to define the base of the Upper Zone. Toward the top of the Upper Zone, particularly adjacent to the top contact, a variant of the Granophyre containing 40 to 50% plagioclase occurs as discrete masses up to several hundred m in thickness. This is known as the Plagioclase-rich Granophyre.

The Lower, Middle, and Upper Zones of the Complex are jointly known as the "Main Mass" and are described herein by Naldrett and Hewins (Chapter 10, this volume).

CHAPTER 10

The Main Mass of the Sudbury Igneous Complex

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ABSTRACT

The units of the Main Mass of the Sudbury Igneous Complex consist of: mafic norite, quartz-rich norite, South Range norite, and felsic norite constituting the Lower Zone; quartz gabbro constituting the Middle Zone; and granophyre of the Upper Zone.

Whole rock geochemical studies show that the rocks of the Complex are anomalously rich SiO_2 . Rare earth element data indicate that the light REE's are enriched; La/Yb N ratios are mainly in the range of 9 to 14, which is high for continental basaltic magmatism; ($\text{Sr}^{87}/\text{Sr}^{86}$) initial ratios are in the range 0.706 to 0.708, which is also high for basaltic magmas dating from 1.85 Ga.

The near similarity of the oxygen isotopic compositions of parts of the Main Mass to those of the Levack Gneiss, Onaping, and McKim Formations are consistent with but do not prove the hypothesis that these rocks may have been partly assimilated by the original magma.

The overall model proposed by the authors is that the Main Mass originated from a fractionated and contaminated magma that consolidated rapidly during a series of complex events to form a funnel-shaped body. The residual liquid of granophyric differentiate was disturbed by subsidence, so that waves of granophyric differentiate spread out across the top of the quartz gabbro, between it, and a layer of plagioclase-rich granophyre adjacent to the roof of the body. Finally, uplift of the South Range occurred by a vertical amount of as much as 5 km relative to the North Range.

INTRODUCTION

Units of the Main Mass of the Sudbury Igneous Complex are summarized in stratigraphic order in Figure 10.1. These units consist of the mafic norite, quartz-rich norite, South Range norite, and felsic norite which together constitute the Lower Zone, the quartz gabbro of the Middle Zone, and the granophyre of the Upper Zone. A distinctive plagioclase-rich facies is found

within the granophyre and, in places, at its upper contact. Not all units are continuous around the Complex. The quartz-rich and South Range norites are restricted to the South Range, the mafic norite occurs only in the North Range, and the felsic norite constitutes the bulk of the Lower Zone in the North Range, but is much more restricted in its development in the South Range.

Walker (1897) was the first to recognize that the Sudbury Igneous Complex was divisible into 2 main parts, norite and granophyre, which he attributed to crystal differentiation. Coleman (1905) mapped the whole Complex and agreed with Walker's interpretation, suggesting that the Complex was a folded, differentiated sill. Knight (1917, 1923) and Phemister (1926) pointed to the rapid upward transition from norite to granophyre and proposed intrusion as a ring dike complex in 2 closely connected episodes, norite followed by granophyre, with mixing taking place at the contact between the two, as another interpretation. Collins (1934, 1937) remapped the Complex and published what is still the most comprehensive major element geochemical study of the rocks of the Main Mass. Collins concluded that all units were the result of *in situ*

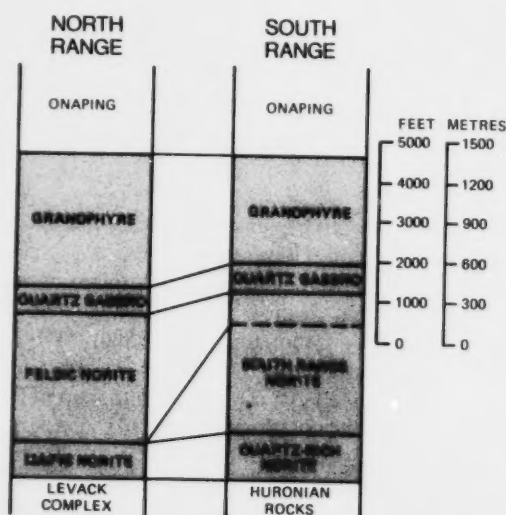


Figure 10.1. Comparative stratigraphic columns through the North and South Ranges of the Sudbury Igneous Complex.

fractional crystallization. Addressing the problem of the SiO_2 -rich bulk composition of the Complex, Wilson (1956) suggested that it is a funnel-shaped intrusion and that the SiO_2 -rich surface rocks are counterbalanced by ultramafic rocks hidden at depth. Stevenson and Colgrove (1968) pointed to felsic inclusions within the Complex and suggested that extensive assimilation of felsic country rocks accounted for the siliceous bulk composition.

Subsequent studies include those of Naldrett and Kullerud (1967), Souch, Podolsky *et al.* (1969), Naldrett *et al.* (1970), Hewins (1971), Gasparrini and Naldrett (1972), Naldrett *et al.* (1972), Peredery and Naldrett (1975), Gibbins and McNutt (1975), Kuo and Crockett (1979), Pattison (1979), and Ding and Schwarcz (1984). It is from these studies that much of the material in this section is drawn.

PETROGRAPHY

The rocks of the Sudbury Igneous Complex differ from those of nearly all other layered complexes in 2 important ways:

1. There is no graded or fine scale igneous layering; hence, features such as scour and fill structures cannot be seen (even if they are present).
2. As will become clear in this, all exposed rocks are very rich in SiO_2 .

Petrographic variations over the North and South Ranges are compared in Figure 10.2.

South Range

The principal rock type of the Lower Zone of the South Range, the South Range norite (Photo 10.1), has a medium- to coarse-grained hypidiomorphic granular texture. The main primary minerals of this rock are cumulus plagioclase and hypersthene, and intercumulus augite, quartz, titaniferous magnetite, and ilmenite. A planar lamination defined by a parallelism of plagioclase grains is apparent in most samples. Naldrett *et al.* (1972) attributed the lamination to the orientation of plagioclase during crystal accumulation. Dark green, strongly pleochroic hornblende mantles both hypersthene and augite. Textural evidence suggests that the hornblende crystallized as a primary mineral. Secondary alteration is both extensive and intensive, with the result that fresh "black" norite occurs as "islands" ranging from a few 10s to a few 100s of m in diameter in a "sea" of completely altered "green" norite. Alteration is particularly severe over the upper one third of the South Range norite where no fresh pyroxene is present.

The quartz-rich norite forms a marginal zone to the Complex along the South Range. The quartz content of this rock increases progressively from the 8

modal %, characteristic of the South Range norite, to more than 20% at the extreme outer margin of the Complex. The true thickness of the gradational zone is 400 to 500 m. Naldrett *et al.* (1970) have shown that the quartz-rich norite, at its outer margin, is distinctly finer grained than the South Range norite, and that its grain size decreases progressively toward the outer contact (Photo 10.2). The fabric of the quartz-rich norite differs from that of the South Range norite in that no igneous lamination is present; plagioclase grains exhibit a random, in some places, almost a radiating growth, and are distinctly more irregular in outline. Uralitization of pyroxene is common, and as much as 25 modal % biotite is present in some samples.

The South Range norite grades, with decrease in hypersthene and increase in augite, quartz, magnetite, ilmenite, and apatite content into the quartz gabbro of the Middle Zone. Fresh pyroxene has not been observed in the quartz gabbro, but textural features suggest that it was all cumulus augite prior to alteration. The titaniferous magnetite of the quartz gabbro appears to be cumulus, and a large, abrupt increase in apatite within the gabbro suggests that this is also cumulus. Naldrett *et al.* (1970) demonstrated that quartz, accompanied by a micrographic intergrowth of quartz and feldspar, increases progressively over the upper third of the quartz gabbro as it grades into the overlying granophyre of the Upper Zone.

The granophyre is very sheared and altered along much of the South Range, but where it is least deformed, it resembles that of the North Range (*see* section which follows for the North Range).

North Range

The rocks of the North Range differ in many respects from those of the South Range. The felsic norite is the principal rock type of the Lower Zone. The rock is coarse grained, has a hypidiomorphic granular texture, and consists of cumulus plagioclase, cumulus hypersthene, and largely intercumulus augite in a proportion of 2:1, biotite, quartz, and quartz-feldspar micrographic intergrowth (*see* Photo 10.2A). The quartz plus micrographic intergrowth averages rather more than 25 modal %. Through the upper one third of the felsic norite, hypersthene is absent, and augite has a tabular form indicating that it is cumulus. At first sight, it would seem logical to draw the upper boundary of the norite at the level where hypersthene disappears, but this limit is difficult to detect in the field because of the altered state of the rocks. The incoming of cumulus magnetite and apatite at the base of the quartz gabbro is much more visible and so is a more convenient boundary than one where hypersthene disappears.

The felsic norite is underlain by the mafic norite, which is characterized by 40 to 60% hypersthene in contrast to the 20% in the felsic norite. Much of the

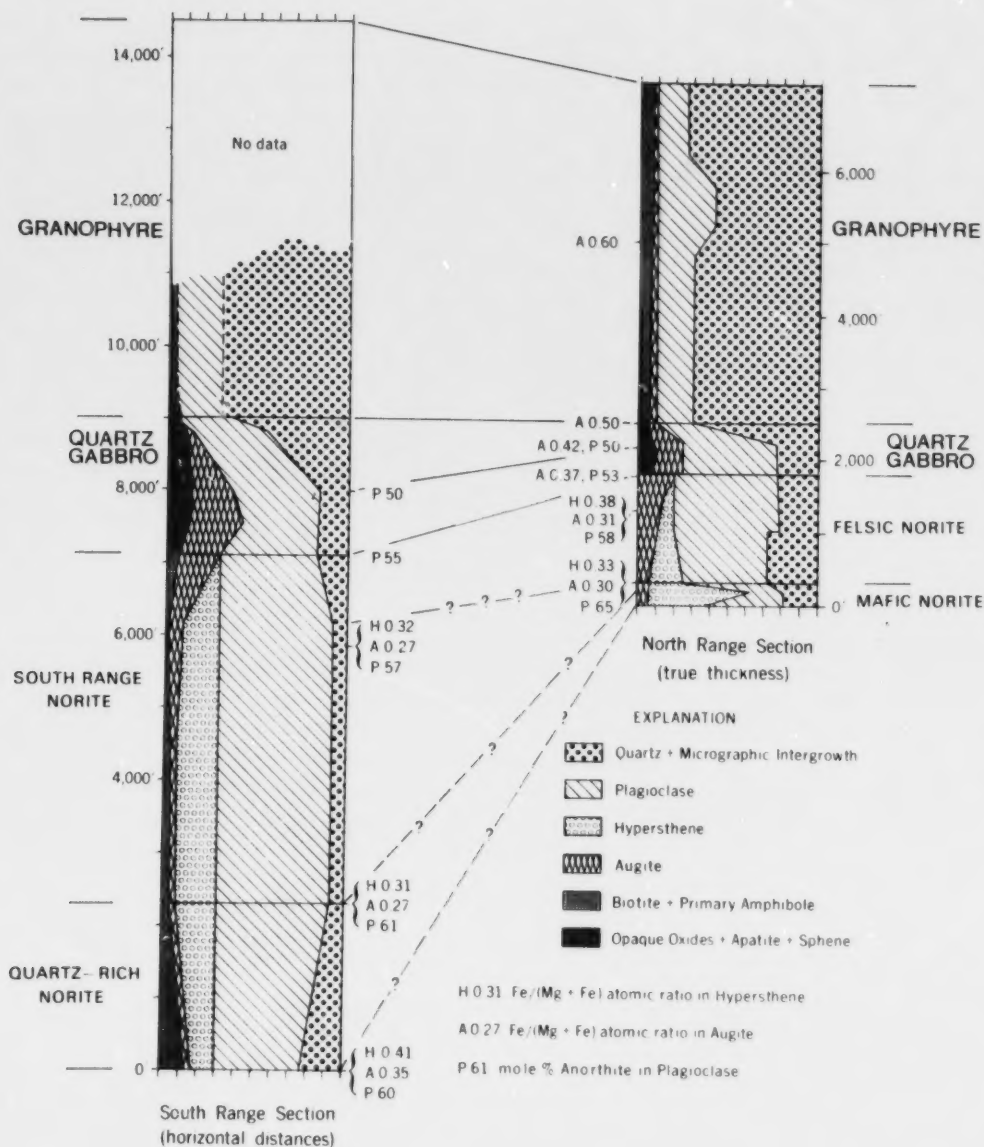


Figure 10.2. Partially idealized diagram illustrating mineralogical variations on sections through the North and South Ranges (after Naldrett *et al.* 1970).

mafic norite is a hypersthene cumulate in which hypersthene grains are enclosed poikilitically by plagioclase. The rock unit, however, grades both upward and downward into a hypidiomorphic-textured mafic norite containing tabular grains of both plagioclase and hypersthene. The mafic norite grades upward into felsic norite with a progressive increase in the proportion of plagioclase through a thickness of 7 to 13 m (Hewins 1971).

The equivalent of the felsic norite on the South Range is not well developed, and is restricted to an interval of perhaps 150 m below the base of the quartz gabbro. In contrast, there is nearly a 500 m true thickness of felsic norite on the North Range.

The felsic norite is overlain by the quartz gabbro (see Photo 10.2B). Opaque oxide minerals are much more abundant (about 9 modal %) in the quartz gabbro of the North Range than in that of the South Range (about 3%), and TiO_2 occurs in magnetite as exsolved lamellae of ilmenite rather than in the discrete ilmenite grains that characterize the South Range. Apart from these distinctions, the quartz gabbro is very similar in both ranges.

The granophyre consists of about 3 parts micrographic intergrowth to 1 part plagioclase. The plagioclase is developed as separate tabular grains dispersed in a matrix of micrographic intergrowth, much of which is in the form of rosettes (see Photo 10.2C). Per-

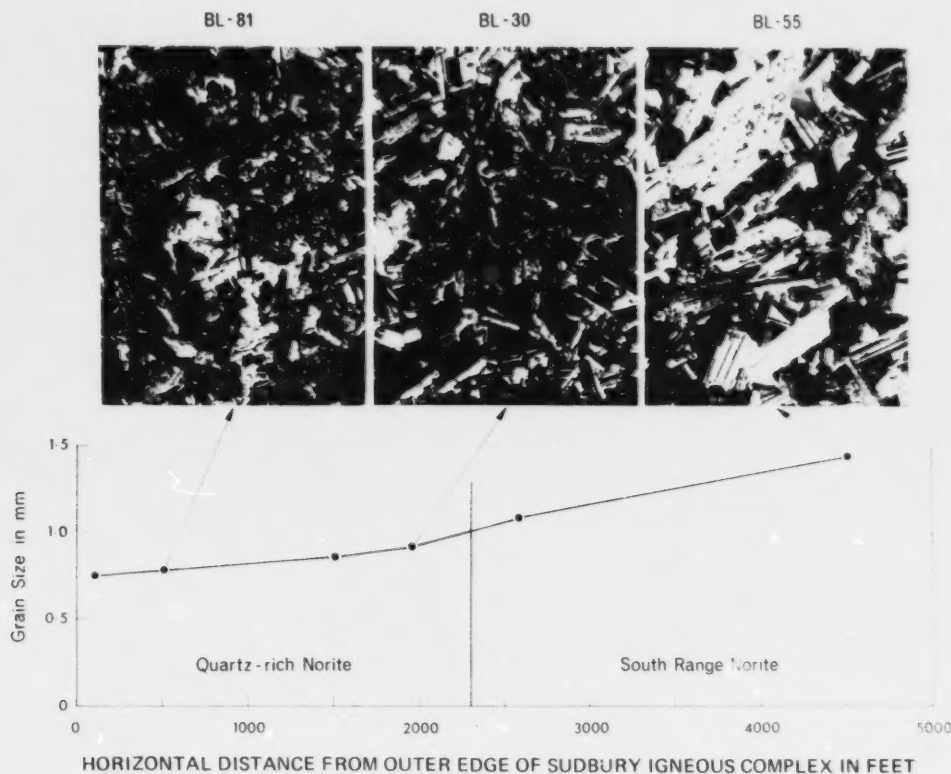


Photo 10.1. Variation in average grain size across the quartz-rich norite and part of the South Range norite. Photographs of each of the samples were taken, enlarged, and the long diagonal of all grains measured (more than 200 grains in each case). Photographs shown are with crossed nicols. 5X

edery and Naldrett (1975) have drawn attention to a plagioclase-rich (35 modal % plagioclase) variant of the granophyre which occurs within 300 m of the upper contact. Modally, chemically, and mineralogically this variant is an extension of the trends of the quartz gabbro, and it appears that the normal granophyre has been injected below and around large masses of this material.

East Range

Naldrett *et al.* (1970) presented data for a traverse across the East Range in MacLennan Township, and pointed out that the rocks are similar in most respects to those of the North Range.

Layering in the Complex

It has already been stressed that fine scale layering is absent from the Complex. Phase layering is present and, on the North Range, is parallel to the Footwall (Figure 10.3). The unavailability of deep drillholes on the South Range has meant that the relationship between the dip of the layering and the Footwall has not been determined. Naldrett *et al.* (1972) showed that the igneous lamination that is so prominent in the South Range norite dips 30°N in contrast to the 40°N dip of

the Footwall contact where Highway 69 cuts across the Lower Zone (Figure 10.4). These authors postulated that this lamination formed parallel to the interface that existed between magma and crystal cumulates, and hence, that it also reflects the attitude of the phase layering.

MINERAL COMPOSITIONS

Pyroxenes

Cryptic variation in pyroxene composition is summarized in Figure 10.2. Overall, the Fe/(Fe + Mg) atomic ratio of hypersthene increases from 0.31 at the base of the South Range norite to 0.38 at the top of the felsic norite. The same parameter for intercumulus augite increases from 0.27 to 0.31 through the same interval, then increases to 0.37 where the augite becomes cumulus at the base of the quartz gabbro; it then continues to increase, reaching 0.50 at the top of this gabbro and 0.60 within the granophyre.

Compositional variation across the quartz-rich norite of the South Range is anomalous (Figure 10.5). While Fe/(Fe + Mg) shows the normal upward in-

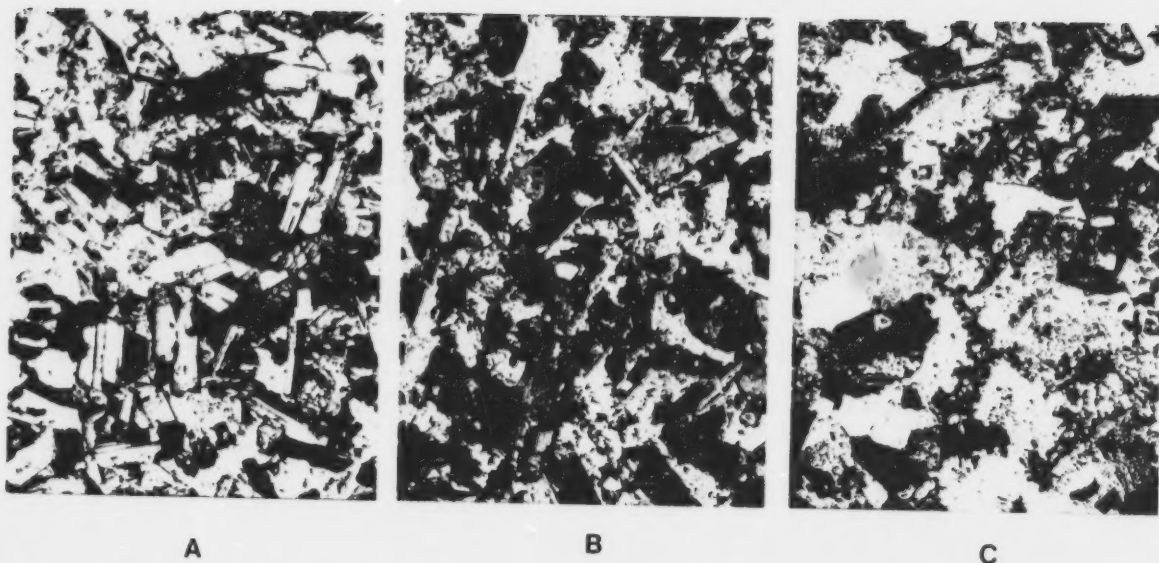


Photo 10.2 A. Felsic norite. S-2509. Crossed nicols. 6.5X. B. Quartz gabbro. This illustrates an extreme example of the cloudy alteration that affects the upper part of this unit. 6.5X. C. Granophyre. Crossed nicols. 6.5X.

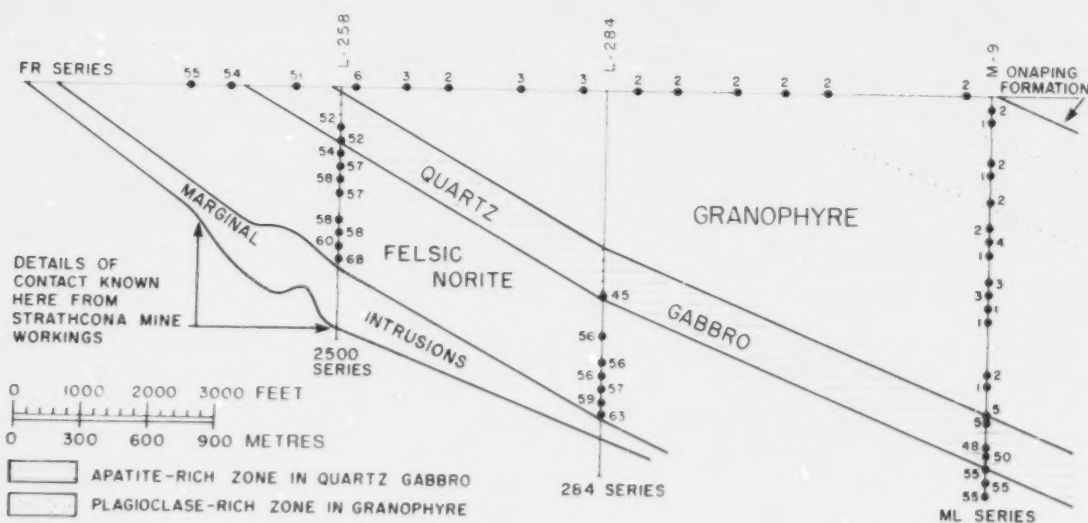


Figure 10.3. Vertical cross-section through the Sudbury Igneous Complex at Strathcona Mine (after Naldrett *et al.*, 1970).

crease through the South Range norite, it shows a downward increase, paralleling the increase in quartz, toward the outer (and lower) margin of the Complex. As Naldrett *et al.* (1970) stressed, this increase is accompanied by an increase in the zoning of Fe and Mg, with the effect that while the composition of the cores of grains is constant, the average composition of the grains becomes steadily richer in Fe.

A downward increase in $\text{Fe}/(\text{Fe} + \text{Mg})$ of the pyroxenes is also present across the mafic norite (Figure 10.6). In this case also, an increase in zoning is apparent as the average composition of the grains becomes more Fe-rich. Another striking feature illustrated by Figure 10.6, is that $\text{Fe}/(\text{Fe} + \text{Mg})$ increases abruptly

from 0.28 at the top of the mafic norite to 0.33 at the base of the felsic norite. This change led Hewins (1971) to conclude that a sequence of cumulates is missing in this interval, and is equivalent to much of the South Range norite.

Plagioclase

As illustrated in Figure 10.2, the anorthite content of plagioclase decreases from An_{61} at the base of the South Range norite to An_{50} halfway up the quartz gabbro. As mentioned above, at and above a well-defined level within the quartz gabbro, the plagioclase is partly altered to epidote, consequently, its An content is de-

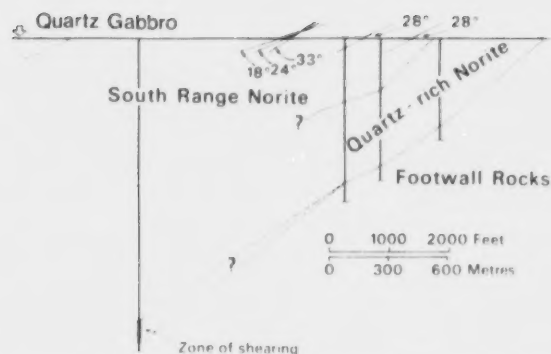


Figure 10.4. Vertical section through the South Range along Highway 69 in Blezard Township illustrating the distribution of the quartz-rich norite and the orientation of igneous foliation of plagioclase in samples collected along the highway (after Naldrett *et al.* 1972).

creased to < 10 mole %. This saussuritization was attributed by Naldrett *et al.* (1970) to a deuteritic reaction.

Direct data on the original composition of plagioclase above this stratigraphic level are lacking, because all of the plagioclase is altered, but Peredery and Naldrett (1975) pointed out that the normative An content of plagioclase decreases abruptly from An₅₀ in the quartz gabbro to An₁₅ to An₂₀ through much of the granophyre, before rising to An₃₅ to An₄₀ in the plagioclase-rich granophyre near the top of the Complex.

Oxide Minerals

Gasparrini and Naldrett (1972) stated that the quartz gabbro contains 1 to 10% of Fe-Ti oxide minerals, with titaniferous magnetite greatly in excess of ilmenite; the felsic norite 0.1 to 2% with ilmenite in excess of magnetite; the quartz-rich norite 0.5 to 1%, largely ilmenite; and the mafic norite 0.5 to 1% oxide, largely magnetite.

Much of the TiO₂ in the oxides occurs as "oxy-exsolved" (Buddington and Lindsley 1964) ilmenite lamellae, hence primary mineral compositions had to be obtained by analyzing both the host and lamellae, estimating their proportions, and then calculating weighted means. Variations in TiO₂ and Cr₂O₃ in magnetite across the section of the North Range studied by Gasparini and Naldrett (1972) are illustrated in Figures 10.7 and 10.8. It was not possible to obtain data on the original composition of the South Range magnetites because the "oxy-exsolved" ilmenite has segregated to such an extent that it now mostly occurs as separate grains, peripheral to the magnetite, and the relative proportions of the 2 cannot be estimated with any certainty. Examination of these figures reveals that TiO₂ in magnetite ranges from 3 to 6 wt% in the mafic norite to 22 to 24% in the granophyre; Cr₂O₃ ranges

from a high of 13.5 wt% in the mafic norite to < 0.5% in the felsic norite and quartz gabbro.

In co-existing grains of the magnetite-ulvöspinel and ilmenite-hematite solid solution series, intermediate members of the solid solutions are characteristic of the rocks of the North Range, while those of the South Range are characterized by co-existing ilmenite and magnetite (Figure 10.9). On the basis of Buddington and Lindsley's (1964) log fO₂-temperature data, the oxide pairs from the North Range appear to have equilibrated down to temperatures of 800° to 1000°C, while those of the South Range have equilibrated to 600°C or below. Even though the effect of MgO and other impurities on the fO₂-temperature relationships of the co-existing phases may invalidate the actual numbers obtained by Gasparrini and Naldrett (1972), these numbers will not invalidate their conclusion that there is a major difference in the temperature down to which equilibrium was achieved on the 2 ranges. Two possible reasons were proposed for the difference. The first was the possible effect on the South Range rocks of the structural and metamorphic disturbance caused by the Grenville Orogeny; the Grenville Front is located only 16 km to the southeast. The second was that the South Range rocks may represent the deeper part of a funnel-shaped complex, a part that was thicker and thus cooled more slowly than the sill-like body represented by the North Range. Gasparrini and Naldrett (1972) were unable to choose between these alternatives, but preferred the latter.

WHOLE ROCK GEOCHEMISTRY

Major Elements

The most comprehensive study of the major element geochemistry of the Sudbury Igneous Complex was that of Collins (1934). Since that time, Muir (1983) has released data, including selected trace elements on the mafic and felsic norites, quartz gabbro, and granophyre.

Collins (1934) concentrated on 4 profiles across the Complex, 2 across the North Range and 1 across each of the East and South Ranges. Chemical variations along his profiles reflect the modal and mineralogical data that have been discussed in preceding sections. By weighting analyses of the norites and the granophyres according to stratigraphic thickness, Collins obtained average compositions for each rock type which he then combined to give the overall norite and granophyre averages listed in Table 10.1. Combining these again according to the surface abundance of the 2 rock types (norite 34.5% and granophyre 62.6%), and omitting from consideration the transition zone which underlies 2.6%, Collins obtained the

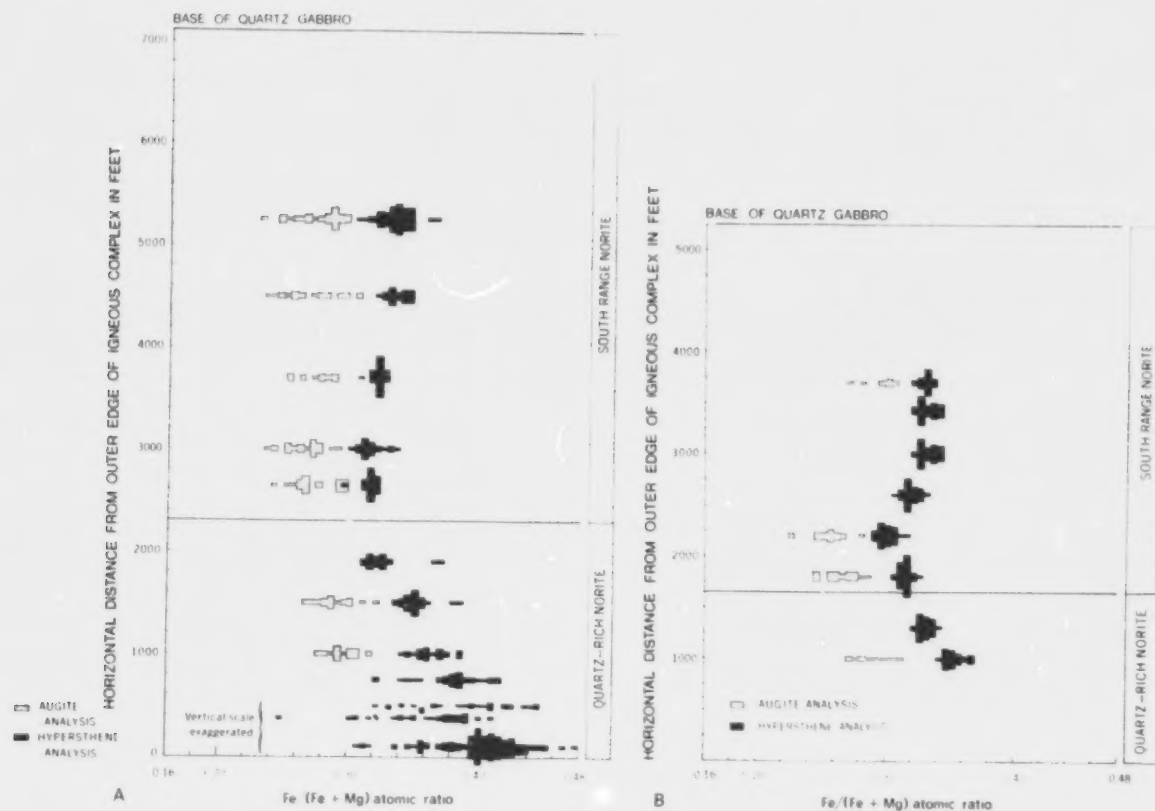


Figure 10.5. Variation in the $\text{Fe}/(\text{Fe} + \text{Mg})$ atomic ratio of hypersthene (black) and augite (shaded) with horizontal distance from the outer edge of the Sudbury Igneous Complex in samples from A. the B'ezard traverse and B. the North Star traverse of the South Range (see Naldrett *et al.* (1970) for location of traverses). The number of analyses falling within an interval of $\text{Fe}/(\text{Fe} + \text{Mg}) = 0.05$ is proportional to the vertical extent of the bar in each case. More than 25 analyses were made of most samples in the case of hypersthene, and in some samples more than 100 analyses were made (after Naldrett *et al.* 1970).

TABLE 10.1: AVERAGE COMPOSITION OF THE SUDBURY IGNEOUS COMPLEX (after Collins 1934)

	Norite	Granophyre	Whole Complex
SiO_2	55.16	67.83	63.14
TiO_2	0.83	0.68	0.74
Al_2O_3	16.86	13.36	14.65
Fe_2O_3	1.94	1.28	1.52
FeO	6.50	4.39	5.17
MnO	0.10	0.07	0.08
MgO	5.17	1.50	2.85
CaO	7.42	2.04	4.03
Na_2O	2.87	3.39	3.20
K_2O	1.35	3.82	2.91
P_2O_5	0.25	0.21	0.23
CO_2	0.15	0.17	0.16
H_2O	1.23	1.21	1.24

average for the entire Complex listed in Table 10.1. The SiO_2 -rich nature of this composition is responsi-

ble for much of the debate about the nature of the Sudbury Igneous Complex.

The high SiO_2 of the Complex is not entirely attributable to fractional crystallization. Naldrett *et al.* (1972) compared the normative proportions of olivine, hypersthene, and quartz in the Sudbury cumulus rocks with those of several other well known layered complexes on the basis of the $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio of the pyroxenes and the An content of plagioclase. The data are shown here in Figure 10.10. All of the rocks of the Sudbury Complex are unusually rich in normative quartz, regardless of whether they come from highly evolved parts of the body or relatively early forming cumulates. It was this observation that lead Irvine (1975) and subsequently Naldrett and Macdonald (1980) to propose that the magma of the Complex had become contaminated by SiO_2 -rich country rocks.

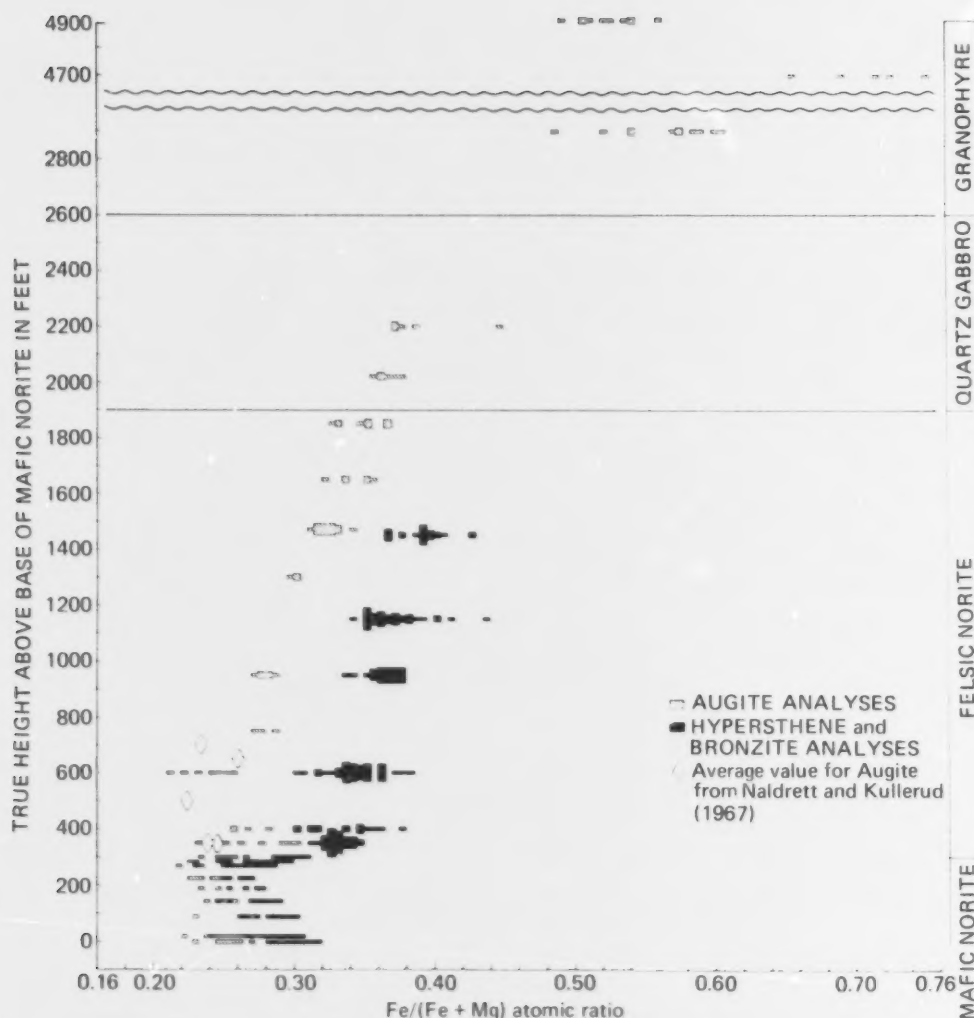


Figure 10.6. Variation in the composition of pyroxenes across the Strathcona section of the North Range of the Complex (after Naldrett *et al.* 1972).

Rare Earth Elements

Average chondrite normalized REE patterns for the norite, quartz gabbro, and granophyre, taken from Kuo and Crocket (1979), are illustrated in Figure 10.11. All of the igneous rocks of the Complex are characterized by light REE-enriched patterns with $(La/Yb)_N$ ratios mostly in the range of 9 to 14. The South Range norite, with an average $(La/Yb)_N$ of 8.8, shows the least LREE enrichment, followed by the felsic norite (average $(La/Yb)_N = 10.51$), the quartz-rich norite (average $(La/Yb)_N = 11$), the mafic norite (average $(La/Yb)_N = 14.3$). The granophyre samples show negative Eu anomalies, whereas the norites have positive values. Kuo and Crocket (1979) pointed out that the early gabbroic cumulates of layered intrusions commonly have total REE concentrations and $(La/Yb)_N$ ratios less than their border facies (which may be

equivalent to the original magma), and that the granophyres are commonly enriched in REE and have higher $(La/Yb)_N$ ratios. The Eu anomalies are also usually what would be expected; the border rocks show little or no anomaly, the plagioclase cumulates show a positive anomaly, and the granophyres show negative anomalies. Qualitatively, the Sudbury results exhibit normal behaviour.

Sr^{87}/Sr^{86} Variation

The Sr isotopic ratios of samples of the Main Mass norite and granophyre were first studied by Fairbairn *et al.* (1960) and subsequently by Fairbairn *et al.* (1965, 1968), Souch, Podolsky *et al.* (1969), and Hurst and Wetherill (1974). Fairbairn *et al.* (1968) interpreted their data, which were mainly on samples of granophyre, to indicate an age of 1.700 Ga. The data of Souch, Podolsky *et al.* based on norites, however,

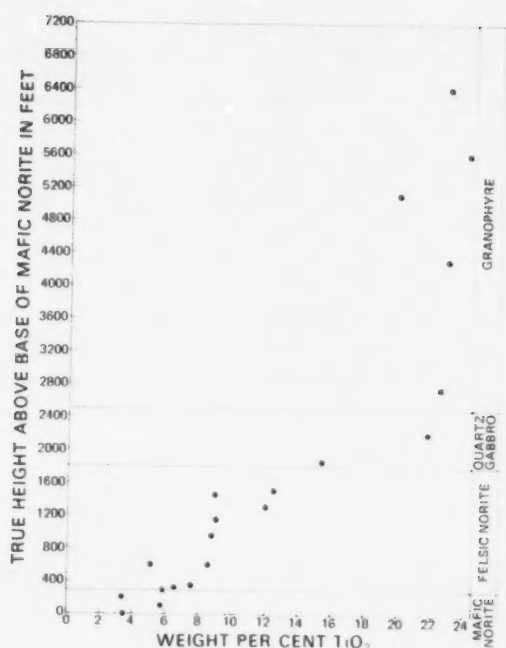


Figure 10.7. Variation in the TiO_2 content of magnetite in rocks of the North Range. Some analyses have been calculated using the abundance of exsolved ilmenite in the magnetite and the composition of both the ilmenite lamellae and the host magnetite (after Gasparrini and Naldrett 1972).

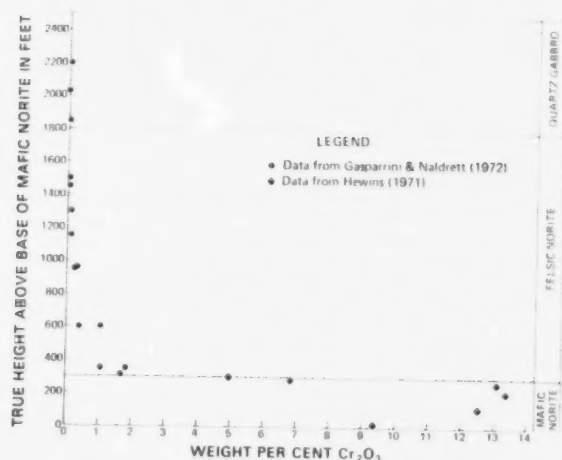


Figure 10.8. Variation in the Cr_2O_3 content in rocks of the North Range. Some analyses have been calculated as discussed under Figure 10.7 (after Gasparrini and Naldrett 1972).

suggest an age of 2.00 Ga, and the Hurst and Wetherill data, also based on norite samples, point to an age of 1.785 ± 0.126 Ga.

The most comprehensive study is that of Gibbins and McNutt (1975). Their samples came from the Blezard traverse along Highway 69 across the South Range, and from the Fecunis-Strathcona area of the North Range. Their data for the norites and grano-

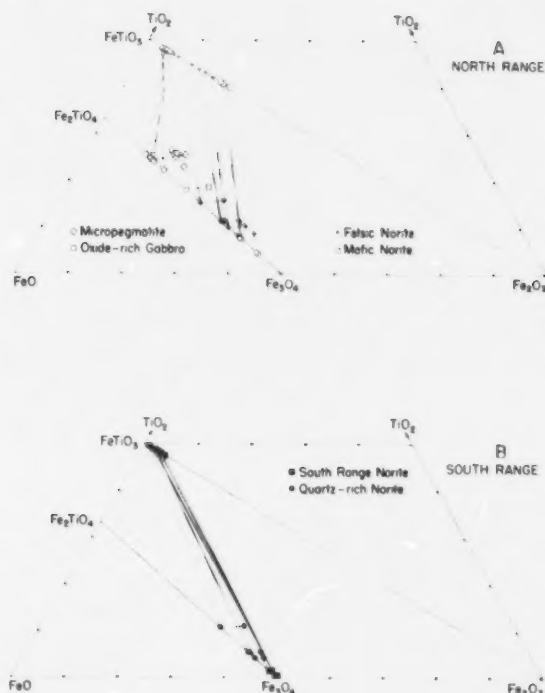


Figure 10.9. The composition of co-existing ilmenite and spinel in rocks of A. the North Range and B. the South Range. Because varying amounts of ilmenite have been recalculated into their analyses, many of the spinel compositions lie off the magnetite-ulvospinel join. Following standard practice, these have been projected back onto the join along lines of constant Fe:Ti atomic ratio (after Gasparrini and Naldrett 1972).

phyre of the North and South Ranges are illustrated in Figure 10.12. Data for the norites define an isochron of 1.956 ± 0.098 Ga with a $(\text{Sr}^{87}/\text{Sr}^{86})$ ratio of 0.7063 ± 0.0004 , while those for the granophyres define an isochron of 1.680 ± 0.062 Ga with a $(\text{Sr}^{87}/\text{Sr}^{86})$ ratio of 0.7083 ± 0.0014 . Comparison of 6 selected samples of South Range norite that were analyzed at McMaster University and with a high precision mass spectrometer at Oxford University indicate ages of 1.893 ± 0.159 Ga and 1.859 ± 0.059 Ga respectively. These norite data are consistent with the latest Pb/U zircon age of Krogh *et al.* (Chapter 20, this volume) of 1.85 Ga. Thus, it seems likely that a $(\text{Sr}^{87}/\text{Sr}^{86})$ ratio for the norite of 0.7067 is probably representative.

The appreciably younger apparent age for the granophyre is consistent with that of Fairbairn *et al.* (1968). Gibbins and McNutt (1975) dismissed on geological grounds the possibility that the granophyre was intruded to 0.2 Ga after the norite, and they explored the possibility that the norite was selectively contaminated with either more radiogenic or less radiogenic Sr. Gibbins and McNutt (1975) discounted the former possibility as inconsistent with their data, and consid-

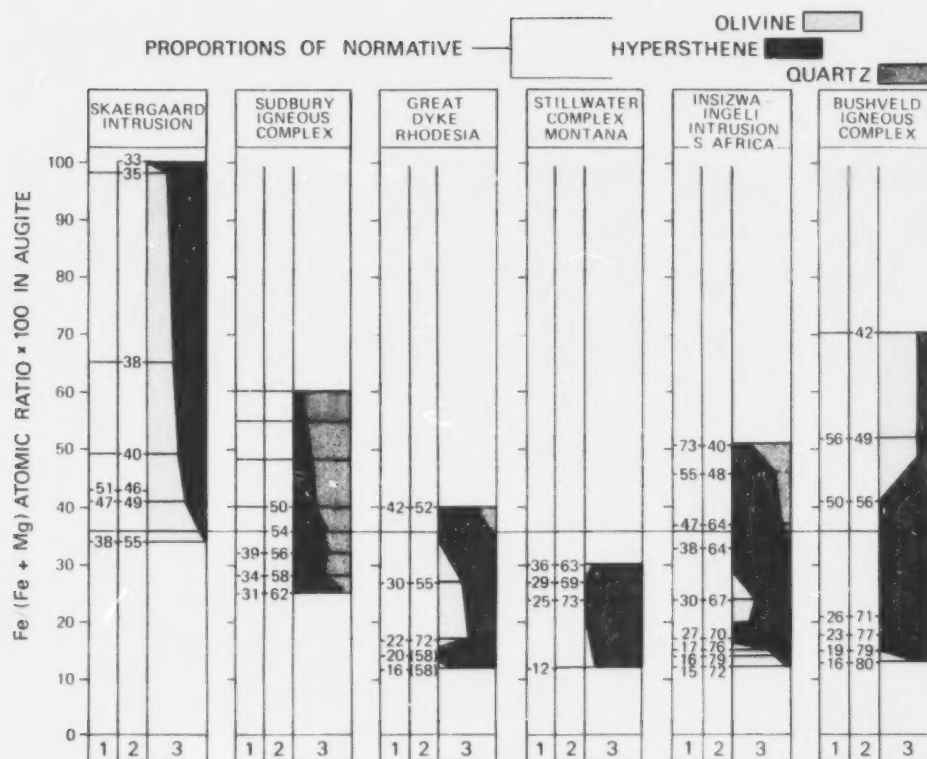


Figure 10.10. Normative proportions of olivine, hypersthene, and quartz in cumulus rocks from a number of well-known layered intrusions compared on the basis of the $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio of their augite. The same ratio of hypersthene (column 1) and the An content of plagioclase (column 2) are also shown for each sample (after Naldrett and Macdonald 1980).

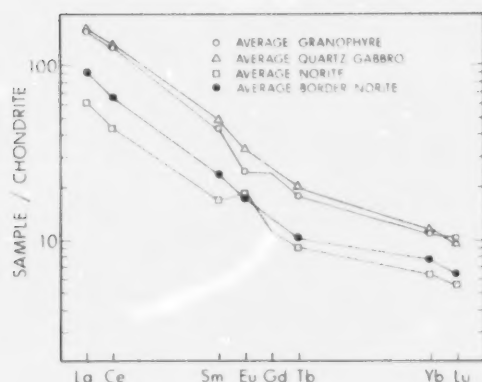


Figure 10.11. Average chondrite-normalized rare earth element fractionation patterns for rocks of the Sudbury Igneous Complex. Normalization values after Haskins *et al.* (1968). (after Kuo and Crockett 1979).

ered that the latter was unlikely to produce an isochron. Gibbins and McNutt (1975) concluded that the most likely interpretation was that Sr in the granophyre was rehomogenized at about 1.680 Ga during the Penokean Orogeny, probably by the fluids responsible for the metamorphic hydrous alteration that Naldrett *et al.* (1970) have reported as affecting this rock.

Naldrett *et al.* (1970) were impressed by the strong influence that stratigraphy had in controlling the saussuritization of plagioclase, and concluded that the alteration was a deuteric feature, occurring as the Complex crystallized. The interpretation of Gibbins and McNutt (1975) would, on the other hand, require the homogenization to post-date consolidation by 0.2 Ga, and thus implies that access of the metamorphic fluids was controlled by a higher permeability in the granophyre than in the norite; something for which there is no evidence at the present time.

$\text{O}^{18}/\text{O}^{16}$ Variation

Ding and Schwarcz (1984) reported data on the $\text{O}^{18}/\text{O}^{16}$ variation in igneous rocks of the Complex and on samples of the Levack Gneisses and the Onaping Formation. Their data are summarized in Figure 10.13. It is seen that the $\delta^{18}\text{O}$ for norite ranges from +5.3 to +8.6 and that for granophyre from +6.3 to 7.1, but that there is little correlation between $\delta^{18}\text{O}$ and SiO_2 . Ding and Schwarcz (1984) pointed out that although the average $\delta^{18}\text{O}$ for the norite is close to that given by Taylor (1968) for typical continental volcanic rocks, the range is greater than observed for fresh Phanerozoic mafic rocks. Ding and Schwarcz (1984) investi-

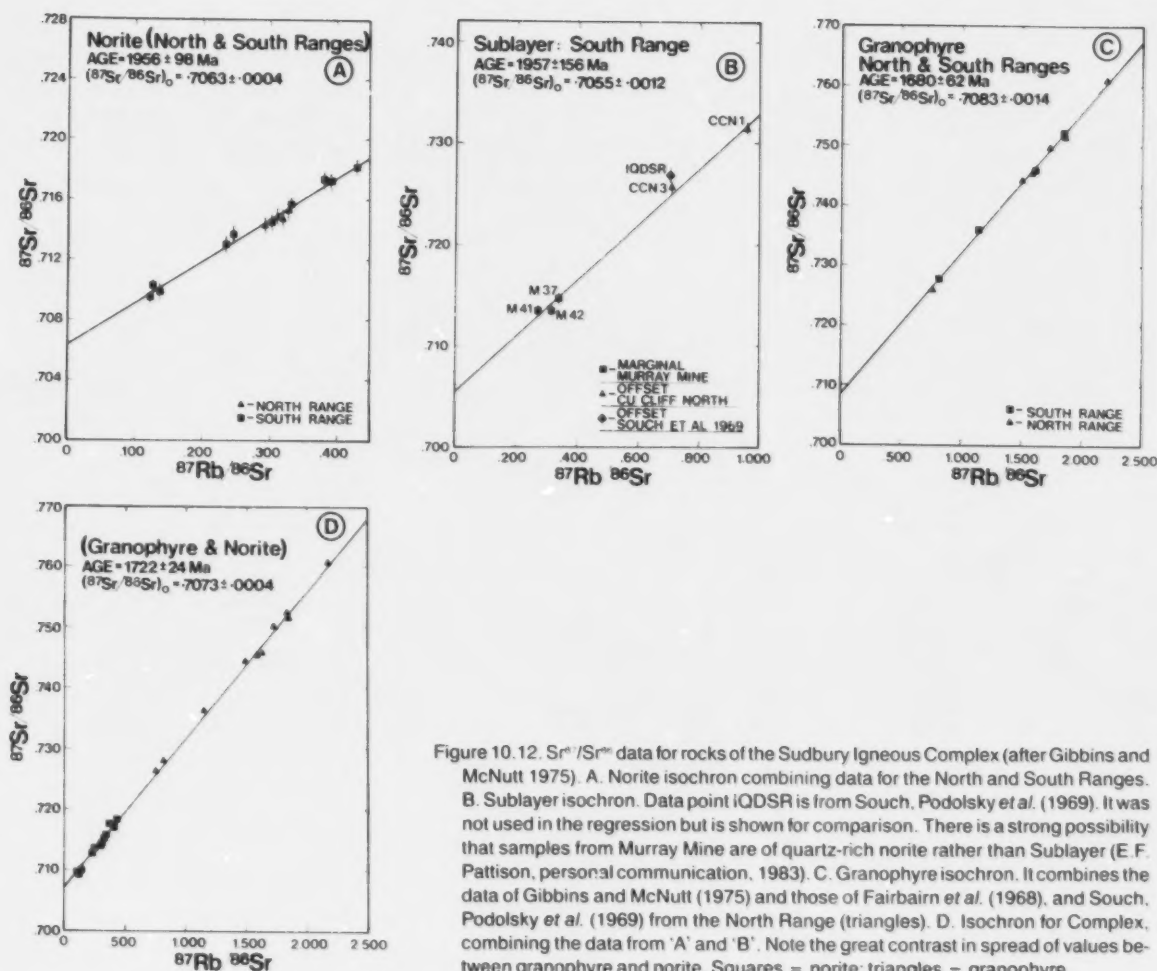


Figure 10.12. $\text{Sr}^{87}/\text{Sr}^{86}$ data for rocks of the Sudbury Igneous Complex (after Gibbins and McNutt 1975). A. Norite isochron combining data for the North and South Ranges. B. Sublayer isochron. Data point IQDSR is from Souch, Podolsky *et al.* (1969). It was not used in the regression but is shown for comparison. There is a strong possibility that samples from Murray Mine are of quartz-rich norite rather than Sublayer (E. F. Pattison, personal communication, 1983). C. Granophyre isochron. It combines the data of Gibbins and McNutt (1975) and those of Fairbairn *et al.* (1968), and Souch, Podolsky *et al.* (1969) from the North Range (triangles). D. Isochron for Complex, combining the data from 'A' and 'B'. Note the great contrast in spread of values between granophyre and norite. Squares = norite; triangles = granophyre.

gated the correlation between $\delta^{18}\text{O}$ and degrees of alteration, but concluded that none exists.

As seen from Figure 10.13, the norites of the South Range are richer in $\delta^{18}\text{O}$ (average $\delta^{18}\text{O} = +7.6$) than those of the North Range (average $\delta^{18}\text{O} = +6.7$), but that the granophyres of the South Range (average $\delta^{18}\text{O} = +7.3$) are much the same as those of the North Range (average $\delta^{18}\text{O} = +7.4$). The norites of the 2 traverses of the North Range are similar (average $\delta^{18}\text{O}$ of northwest traverse = +6.8; average $\delta^{18}\text{O}$ of northeast traverse = +6.5), but the granophyres are distinct (average $\delta^{18}\text{O}$ of northwest traverse = +7.9; average $\delta^{18}\text{O}$ of northeast traverse = +6.8). The difference in the granophyre parallels that in the overlying Onaping Formation (average $\delta^{18}\text{O}$ of northwest traverse along Highway 144 = +8.7; that of 7 samples from northeast traverse, but omitting 1 very atypical value of +12.1, = +7.2).

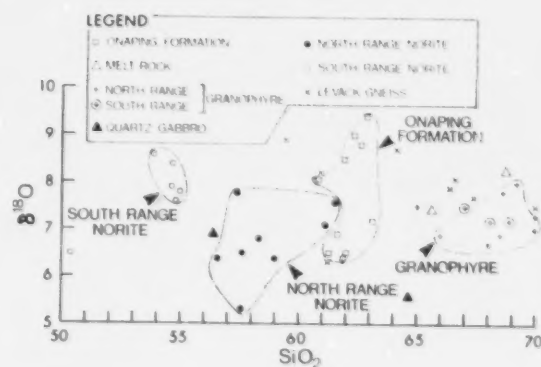


Figure 10.13. Variation in $\delta^{18}\text{O}$ of rocks of the Sudbury district when compared on the basis of their SiO_2 content (after Ding and Schwarcz 1984).

The near similarity between the oxygen isotopic composition of the norite and the Leveck Gneiss is

consistent with the hypothesis that the high SiO_2 characteristic of the norites reflects assimilation of the gneiss. Ding and Schwarcz (1984) suggested that the heavier oxygen in the norites of the South Range is due to the O^{18} -rich McKim Formation present in this area having been assimilated by this norite.

The fact that the difference between the $\delta^{18}\text{O}$ values of the granophyre of the northwest and northeast traverse is paralleled by the differences between the overlying Onaping Formation in each locality, without the values actually reaching the same level, suggests that assimilation of the Onaping Formation was a major factor in the formation of the granophyres. Ding and Schwarcz (1984) argued against this possibility, stating that while mixing of Onaping Formation and norite could account for the isotopic composition of the granophyre, it would not account for the major element composition. The authors have no argument with this interpretation, but point out that the problem of the granophyre is one of overabundance, and the authors believe that fractional crystallization and assimilation both have contributed to its formation.

DISCUSSION

This discussion will focus on 4 major aspects of the Sudbury Igneous Complex:

1. a model for its emplacement
2. the relationship between the norite and granophyre and the nature of the transition between them
3. the composition of the original magma emplaced at Sudbury
4. lastly, the degree to which assimilation of country rocks has affected the composition of the Complex

A Model for the Complex

Three main models have been proposed for the Complex:

1. that it is a folded differentiated sill
2. that the norite and granophyre were intruded separately as ring dikes
3. that it is a funnel-shaped intrusion

The cryptic variation of pyroxene and plagioclase compositions that has been documented to extend from the Lower and Middle Zones is evidence that the Complex is a differentiated body and not a ring dike complex. The parallelism of the phase layering with the Footwall of the Complex on the North Range is suggestive that the body is a sill. However, the irregular distribution of plagioclase-rich layers in the granophyre, coupled with irregularities in the upward variation in the $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio of augite through the granophyre, indicate that the Complex is not a sim-

ple *in situ* differentiate. The very felsic average composition, if this is calculated on the basis of the geometry of a folded sill, also argues against such a simple interpretation. The observation that the igneous lamination on the South Range dips north at a shallower angle than the Footwall of the Complex should be treated with caution as an indicator of the attitude of phase layering, but is suggestive that this part of the intrusion resembles a funnel rather than a sill.

Naldrett *et al.* (1970, 1972) sought to rationalize the indications that the North Range is sill-like and that the South Range is funnel-like with a model that the body is a funnel-shaped intrusion that passed upward and outward into a sill. Naldrett *et al.* (1970, 1972) cited statements by Stevenson and Colgrove (1968) and Souch, Podolsky *et al.* (1969) that much of the South Range had been uplifted 5 km or more with respect to parts of the North Range, and suggested that the present erosion level exposed a deeper, funnel-shaped segment on the south and a shallower, sill-like segment on the north.

Kuo and Crocket (1979) pointed out that their REE data were consistent with the Complex originating as a result of the fractional crystallization of a magma close in its REE content to that of the border (mafic and quartz-rich) norites. Such an origin would account for the increase in $(\text{La}/\text{Yb})\text{N}$ ratio from the South Range norite, through felsic norite and quartz gabbro to granophyre. The positive Eu anomaly of the norites implies that they are plagioclase cumulates, whereas the negative Eu anomaly of the granophyres suggests that they have formed from magma depleted in Eu by plagioclase fractionation. Kuo and Crocket (1979) estimated that 55% of magma represented by the border norites would have to crystallize as plagioclase to produce the magnitude of the Eu anomaly that is present in the granophyre.

The Norite-Granophyre Transition

Peredery and Naldrett (1975) emphasized the abrupt transition from quartz gabbro to granophyre, but pointed out that if the granophyre was removed, the transition from felsic norite to quartz gabbro to plagioclase-rich granophyre was quite smooth in major element chemistry, normative plagioclase composition, and $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio in the pyroxenes. These authors suggested that the granophyre is an extreme differentiate of the Sudbury magma, and that its present distribution is the consequence of a late stage re-injection and redistribution along or close to the top of the Complex. Their postulate accounts for the irregular distribution of the plagioclase-rich granophyre and for the irregular variation of $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios in augite in the normal granophyre. The re-injection presumably occurred while a zone of granophyric liquid still existed at or close to the upper contact of the Complex.

It does not appear likely that the re-injection post-dated intrusion of the Complex by 0.2 Ga; therefore, it would not seem to account for the Sr/Rb age data and indicates a much younger age for the granophyre.

Kuo and Crocket (1979) calculated from Eu anomalies that the Sudbury magma would have had to have been 75% crystallized before it reached a granophyric composition, hence there should be 3 times as much norite as granophyre. This result does not accord with a simple sill model and Collin's estimate of the proportions of the surface area of the Complex underlain by norite and granophyre. It suggests, therefore, that the granophyre is disproportionately abundant at the present level of erosion and is consistent with the presence of a hidden, counterbalancing, possibly funnel-shaped, mafic or ultramafic part of the Complex.

Kuo and Crocket (1979) pointed out that for the transitional quartz gabbro to be, as proponents of the ring dikes hypothesis have maintained, a product of linear mixing of noritic and granophyric magmas, it would require a very large amount of border norite magma to lower the Eu anomaly of the granophyre to the anomaly value observed in the quartz gabbro. In such a case, the remainder of the REE pattern should be characteristic of the norite pattern, but this is not what is observed. The quartz gabbro pattern resembles that of the granophyre, except in its Eu anomaly. Kuo and Crocket, therefore, concluded that the quartz gabbro is not a mixture of 2 magmas, but a fractionated rock in which the negative Eu anomaly has been cancelled out by the presence of some cumulus plagioclase.

Composition of the Sudbury Magma

Naldrett *et al.* (1970), interpreted the quartz-rich norite to be a fairly rapidly cooled rock, because of:

1. the zoned nature of the hypersthene
2. cores of the hypersthene grains have a consistent Fe/(Fe + Mg) ratio of about 0.30
3. the quartz-rich composition
4. the finer-than-normal grain size

These authors suggested that minerals had essentially grown *in situ* from the magma immediately around them. The rock would thus approximate the composition of the Sudbury magma at a particular stage in its fractionation. The inward gradation into the South Range norite was interpreted to reflect the progressive change from an environment of closed system crystallization to one in which cumulus processes had operated.

This change also underlies the progressive downward changes in the texture of the North Range mafic norite from poikilitic to hypidiomorphic, and the accompanying decrease in the proportion of bronzite, the

increase in the average Fe/(Fe + Mg) ratio of bronzite, and the increase in the bronzite zoning.

The outermost parts of the quartz-rich and mafic norites are, therefore, possible samples of the Sudbury magma, modified perhaps to some extent by cumulus processes, and possibly by *in situ* or nearly *in situ* contamination. The mafic norite is clearly much richer in mafic components than the quartz-rich norite. Hence, the mafic components do not represent the same magma, but may represent different stages in the differentiation of the same magma.

The Mg number of the quartz-rich norite is close to 0.61. It is believed that primary magmas, derived directly from the mantle and therefore in equilibrium with mantle olivine (Fo = 90 mole %), should have an Mg number of about 0.73. The magma that gave rise to the quartz-rich norite of the Sudbury Igneous Complex was therefore clearly not primary, but had had a pre-history of fractional crystallization. This pre-history may be recorded in the inclusions in the Sublayer, which are discussed in the next section.

Assimilation and the Main Mass Magma

The SiO₂-rich nature of the Sudbury Igneous Complex has been stressed in this chapter. Also the possibility that the SiO₂-rich nature is due to contamination by felsic country rocks has been stressed. The high (Sr⁸⁷/Sr⁸⁶) ratio of the Sudbury norites of 0.7067 is consistent with this interpretation, although it might alternatively have been inherited from an Sr⁸⁷-enriched part of the mantle. The high total REE content and high (La/Yb)_N ratio of the border norites, and complementary nature of the cumulus norite and granophyre patterns, are also suggestive that the Sudbury magma had achieved a trace element signature indicative of contamination before it was emplaced into its present position.

The data of Kuo and Crocket (1979) on the rocks of the Onaping Formation indicate that these rocks have a lower REE content and a generally smaller negative Eu anomaly than the granophyre. Thus, assimilation of the Onaping Formation cannot be called upon to account for differences between the granophyre and underlying norite; rather, assimilation of Onaping Formation rocks would be expected to de-emphasize these features. Kuo and Crocket (1979) pointed to a slight and somewhat erratic upward decrease in the negative Eu anomaly in their North Range granophyre samples, suggesting that this was consistent with an increasing degree of Onaping assimilation. However, these authors did not document the plagioclase content of their samples. These samples might include some plagioclase-rich granophyre. Any additional plagioclase would be expected to have a marked depressive

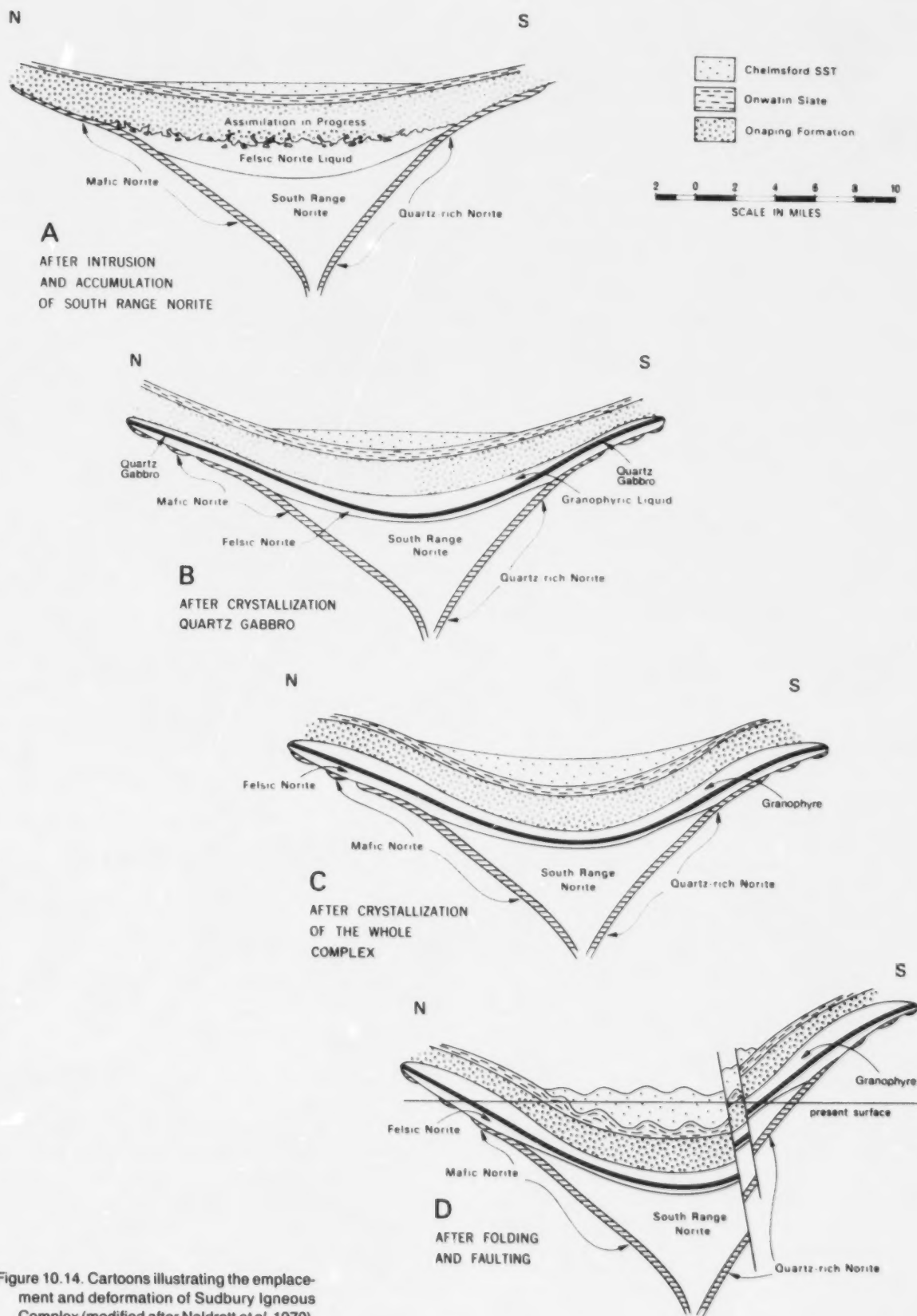


Figure 10.14. Cartoons illustrating the emplacement and deformation of Sudbury Igneous Complex (modified after Naldrett *et al.* 1970).

effect on the Eu anomaly and could account for the trends referred to by Kuo and Crocket (1979).

Ding and Schwarcz's (1984) oxygen isotope data on the North Range norites are consistent with, but certainly do not prove the hypothesis that Levack Gneiss has been assimilated by the Sudbury magma. The heavier isotopic signature of the South Range norites is also consistent with, but does not prove, assimilation of the McKim Formation which forms the country rock along much of the South Range. Contrary to Ding and Schwarcz (1984), it is suggested here that some of the difference in oxygen isotopic composition between granophyres from different localities on the North Range can be equated with differences in the overlying Onaping Formation. Thus, assimilation, coupled with fractional crystallization of the Sudbury magma, is responsible for the difference in oxygen isotopic composition.

Overall Model

An interpretation for the origin of the Main Mass of the Sudbury Igneous Complex preferred by the authors is that it is the consequence of the intrusion of a body of fractionated and contaminated magma up toward and then along an unconformity between the underlying Huronian Supergroup and Archean rocks and the base of the Onaping Formation. This was not a simple process of intrusion of a single homogeneous magma. The contrast between the more primitive mafic norite on the North Range and the more fractionated, quartz-rich norite on the South Range is evidence of this. The magma started to fractionate, leaving the quartz-rich norite as a marginal facies on the South Range (Figure 10.14A). This early crystallization of the lower part of the Complex probably occurred well below the unconformity, perhaps deep in the cone of a funnel-shaped intrusion. Crystallization of the South Range norite, accompanied perhaps by continued contamination, gave rise to a more fractionated magma which then spread out away from the funnel-shaped centre along the unconformity to produce a peripheral sill, which is preserved in the North and East Ranges (Figure 10.14B).

A more primitive derivative of the same magma had previously been intruded in the North Range (to form the mafic norite), but it appears that either it was withdrawn before completing its crystallization, or some of its products were scoured away, since there is a pronounced discontinuity between the mafic and felsic norites of the North Range, along which much of the equivalent of the South Range norite is missing.

Fractional crystallization within the peripheral sill produced the felsic norite, quartz gabbro, plagioclase-rich granophyre, and a residual liquid of granophyric composition. Before this crystallization was complete, structural readjustments in the magma chamber,

perhaps associated with subsidence at the centre of the structure, resulted in one or more waves of granophyric differentiate spreading out across the top of the quartz gabbro, between it and the plagioclase-rich granophyre. This gave rise to a large part of the granophyre that one sees today (Figure 10.14C). Finally, uplift of the South Range, mainly along faults that run parallel to the long axis of the Sudbury Basin, then exposed a deep section of the Complex along the South Range, including the South Range norite of the funnel. This section is deeper than that exposed along the North and East Ranges (Figure 10.14D).

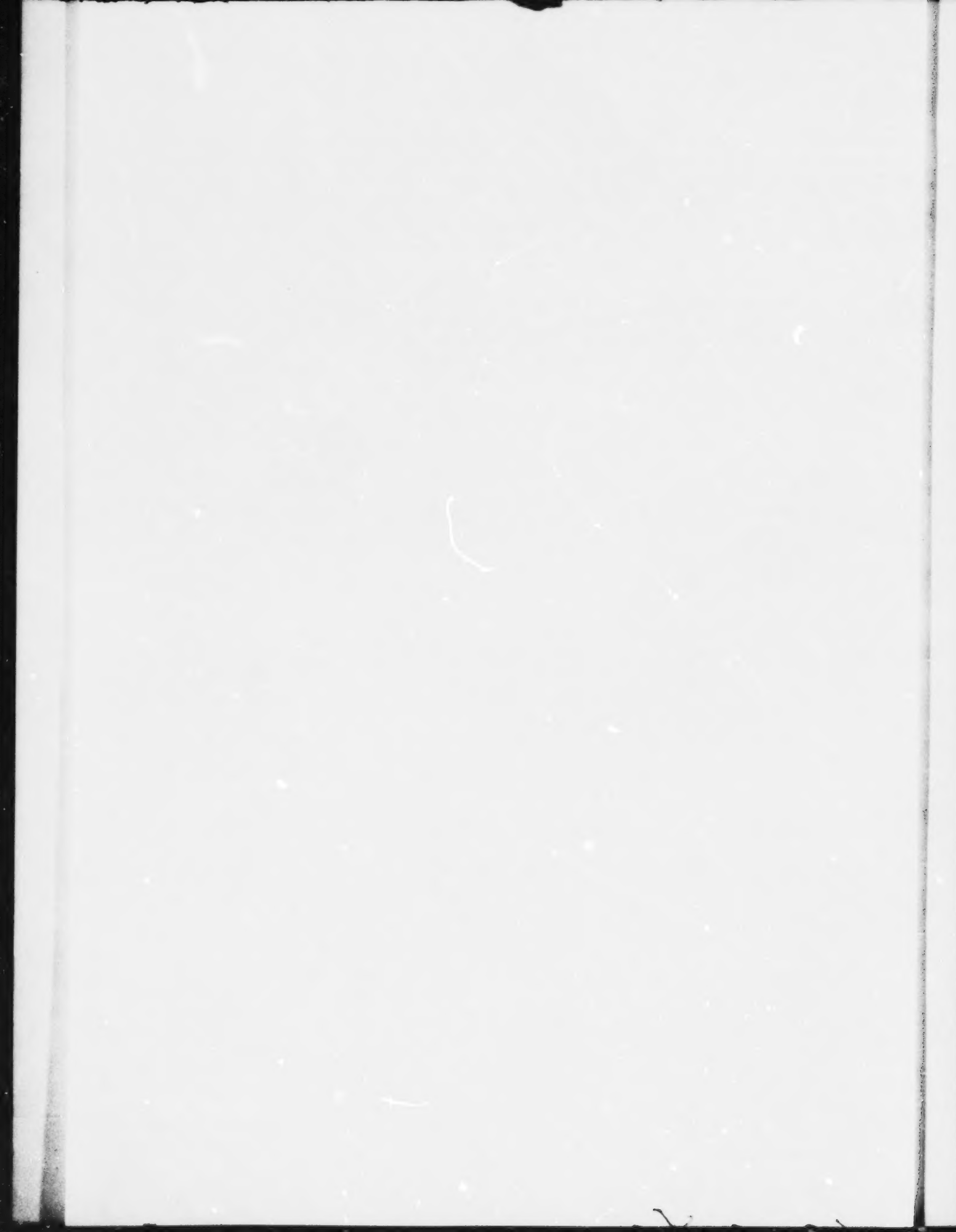
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CHAPTER 11

The Contact Sublayer of the Sudbury Igneous Complex

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ABSTRACT

The Contact Sublayer is a fine- to medium-grained noritic to gabbroic rock that occurs around much of the outer margin of the Sudbury Igneous Complex as discontinuous 'enses and as a filling for the Offset Dikes. The Contact Sublayer is by far the most important rock unit of the Sudbury Igneous Complex in so far as Ni-Cu mineralization is concerned.

Major element geochemistry studies indicate that the Contact Sublayer is rich in K₂O and SiO₂ compared to continental tholeiitic basalts having similar MgO contents.

The textures of the rocks indicate that they were formed as a result of the *in situ* crystallization of a magma. No direct evidence exists for fractional crystallization or gravitational differentiation. Abundances and within suite variations of incompatible

elements are, however, explicable in terms of a model involving the extensive bulk assimilation of crystallized rock by Contact Sublayer magma coupled with fractional crystallization.

Inclusions in the Contact Sublayer are of 2 kinds, one is adjacent country rocks and representatives of a suite of mafic to ultramafic rocks, possibly derived from a hidden layered complex.

Observations bearing on the relative ages of the Sublayer and the Main Mass suggest that both magma types were intruded simultaneously, one slightly ahead of the other and *vice versa* at different localities.

INTRODUCTION AND DEFINITION

The term "quartz diorite" has long been used at Sudbury to describe a rock type that occupies dike-like

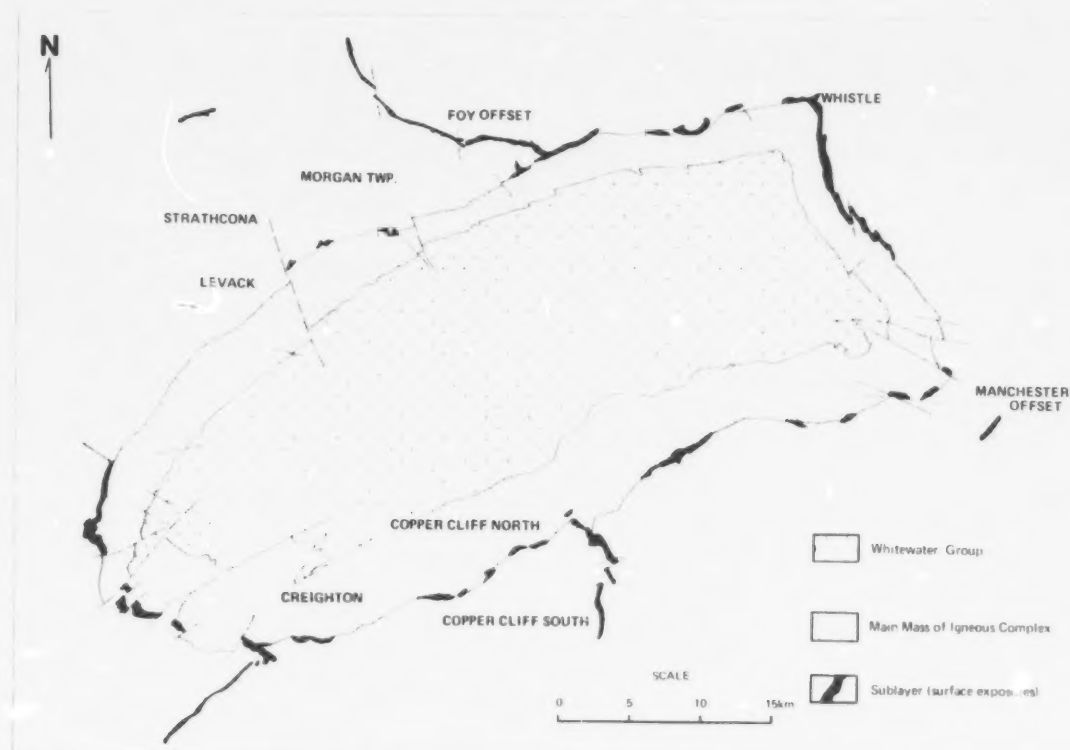


Figure 11.1. Sketch Map of the Sudbury Igneous Complex showing the distribution of the Contact Sublayer (modified after Souch, Podolsky *et al.* 1969).

protuberances (Offset Dikes) in the Footwall along the South Range of the Sudbury Igneous Complex, and as such serves as a host to much sulphide ore (Yates 1948). Naldrett and Kullerud (1967) showed that a rock quite distinct from the norites of the Main Mass of the Sudbury Igneous Complex was the igneous rock most closely connected with ore at the Strathcona Mine. Naldrett and Kullerud (1967) termed this the "xenolithic norite". Souch, Podolsky *et al.* (1969) showed that the association of a distinctive mafic igneous rock with sulphide mineralization was a widespread phenomenon along the base of the Main Mass of the Complex, and they called this the "igneous sublayer", presently known as the Contact Sublayer. The distribution of the Contact Sublayer is shown in Figure 11.1. The Contact Sublayer occurs around much of the outer margin of the Complex as discontinuous lenses and also as a filling for the Offset Dikes. This section is concerned with that part of the Sublayer marginal to the Complex and exclusive of the part of the Sublayer in the dikes, in other words, the Contact Sublayer.

Naldrett and Kullerud (1967) made the point that the proportion of sulphide in the Contact Sublayer was too high to have all been in solution in the magma, if the Contact Sublayer had been intruded separately from the Main Mass of the Complex. Therefore, the

Contact Sublayer must have been emplaced as a mixture of magma plus liquid sulphides. Much of the Contact Sublayer also is characterized by xenoliths. Some of these are identifiable as country rocks; others constitute a suite of ultramafic and mafic rocks of debatable source.

In brief, the Contact Sublayer is a fine- to medium-grained igneous rock composed of hypersthene, augite, and plagioclase, with minor, but variable amounts of quartz, micrographic intergrowths, and iron oxides. Sulphide minerals occur in amounts ranging from traces to more than 60 modal %. The rock texture ranges from intersertal to subophitic, and features small, generally randomly oriented plagioclase grains interstitial to, or partly enclosed by, somewhat larger pyroxene grains. A wide variety of xenoliths are common constituents.

Following the initial papers of Naldrett and Kullerud (1967) and Souch, Podolsky *et al.* (1969), Hewins (1971) documented the Contact Sublayer over a part of the North Range; Rae (1975), Scribbins (1978), and Scribbins *et al.* (1984) described the inclusions in the Sublayer; Pattison (1979) described the Sublayer in general; and Rao *et al.* (1983) studied the major and trace element geochemistry.

DISTRIBUTION AND FACIES OF THE CONTACT SUBLAYER

Along the North Range, the Contact Sublayer is closely associated with plagioclase-rich rocks that form the various facies of the Footwall Breccia. Its characteristics in this area have been thoroughly documented by Naldrett and Kullerud (1967) and Hewins (1971) in the Strathcona-Fecunis area, and by Pattison (1979) at the Whistle Property at the extreme northeastern corner of the Complex and along the Foy Offset.

The Contact Sublayer is much less well documented along the South Range. Here, it can generally be distinguished from the Main Mass norite by its larger content of sulphide minerals, a difference that is not as clear in the North Range.

Figure 11.2 illustrates the distribution of the Contact Sublayer at the Strathcona Mine. The Contact Sublayer is in sharp contact with the overlying mafic and felsic norites. The content of sulphide minerals and inclusions increases downward. At the basal contact of the Contact Sublayer, there is locally a gradation, with increase in plagioclase and quartz, into the matrix of the Footwall Breccia.

A Footwall protrusion filled by the Contact Sublayer at the Whistle Property at the northeastern corner of the Sudbury Structure (Pattison 1979), is illustrated in Figure 11.3. The distribution of rock

types shows an outward zoning. Close to the Main Mass norites, the Contact Sublayer is orthopyroxene rich, and some olivine is present. This is the only place at Sudbury where olivine has ever been observed in rocks belonging undisputedly to the Complex. The proportion of mafic minerals decreases outward along the protrusion as the Contact Sublayer grades first into the normal variant and then into a quartz-rich type. Quartzose Contact Sublayer rocks also flank the more mafic varieties on either side. Xenoliths and sulphide minerals occur throughout much of the Contact Sublayer at the Whistle Property.

The Foy Offset (Pattison 1979; Grant and Bite, Chapter 12, this volume) shows a somewhat similar variation along its length (Figure 11.4) grading from normal Sublayer into a quartz-rich variant that alternates with a Footwall Breccia. According to Pattison (1979), the breccia is very similar in composition to the igneous-textured Contact Sublayer. Near its junction with the felsic norite, the normal Contact Sublayer is flanked by more quartz-rich material, and toward the end of the Foy Offset, more than 10 km from the contact with the Main Mass of the Complex, zones are present in which a central core of sulphide and xenolith-rich material is flanked by sulphide-rich and xenolith-poor material. The Nickel Offsets Mine was developed on one of these zones. Pattison described the Creighton Embayment as an example of Contact Sublayer in the South Range. Here, the embayment is a trough-like depression in the Footwall that is mostly

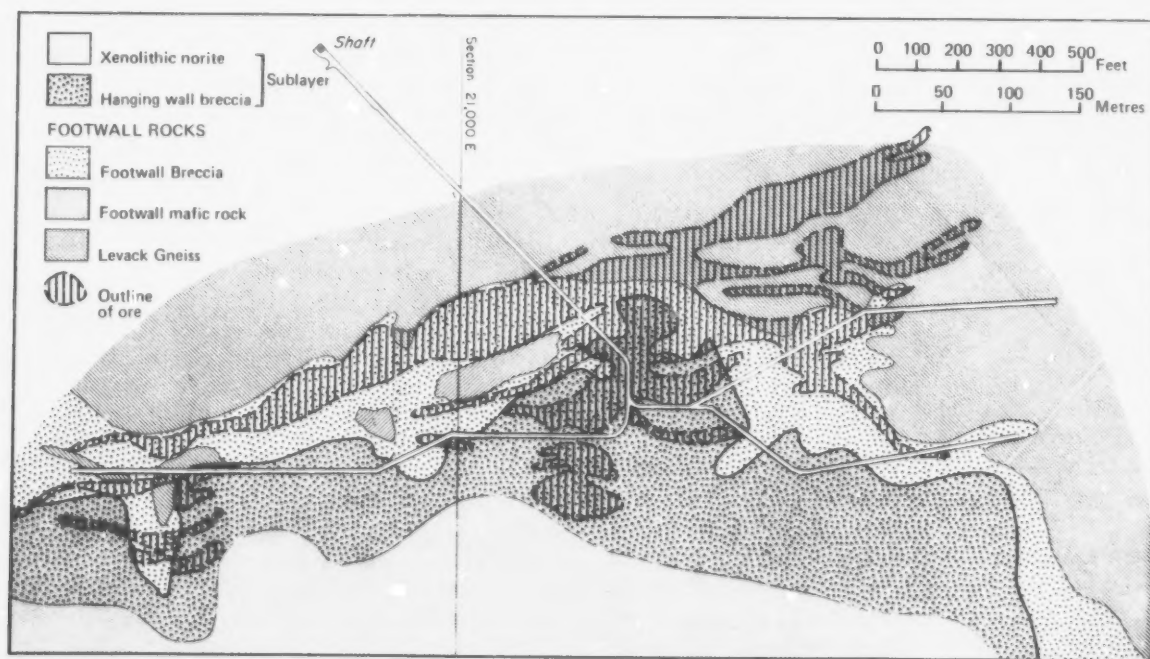


Figure 11.2. Plan of the 2250 level of the Strathcona Mine illustrating the distribution of the Contact Sublayer (after Naldrett and Kullerud 1967).

filled with xenolith-bearing and sulphide-bearing Main Mass quartz-rich norite. The Contact Sublayer occupies the margins of the trough, forming a sheet up to 150 m thick. Pattison (Figure 11.5) drew the boundary between Contact Sublayer and Main Mass norite, apparently on the basis of the abundance of sulphide. The personal experience of one of the authors, A.J. Naldrett, is that this boundary is difficult to see in outcrop or drillcore. The distinction appears to be merely one made on the amount of sulphide present and appears not to be related to any difference in the texture or silicate mineralogy of the rocks. Pattison presented a profile of $\text{Fe}/(\text{Fe} + \text{Mg})$ variation for pyroxenes through the Contact Sublayer at the Creighton Mine

(Figure 11.6) that is very similar to that presented by Naldrett *et al.* (1970) across the quartz-rich norite (see Figure 10.3A, this volume). There is no room for quartz-rich norite between Contact Sublayer and South Range norite in Pattison's profile, and it appears that the Contact Sublayer occurs in place of the quartz-rich norite. Photographs of the fabric of the Contact Sublayer given by Pattison for the South Range are also reminiscent of those of the outer parts of the quartz-rich norite (see Photo 10.1, this volume). In our opinion, further work is required to define the distinction between the Contact Sublayer and the marginal phases of the Main Mass norite on the South Range.

There is some evidence that the Sublayer consists of several intrusive facies. One of the authors, Burkhard O. Dressler, recognized 3 of these at the base of the Main Mass of the Complex. Several Contact Sublayer facies are also present in Offsets, for example, the Copper Cliff Offset (G.G. Morrison, Geologist, Inco Metals Limited, personal communication, 1983).

The oldest facies is seen as the main sulphide-bearing Contact Sublayer unit, and most of this chapter is concerned with this unit. It is characterized by mafic, ultramafic, and sulphide xenoliths that are characteristically subrounded to spherical, and 1 cm to several m in diameter (Photo 11.1). Sulphide minerals also occur as disseminations, or as an almost massive sulphide matrix. The age of this oldest Contact Sublayer facies with respect to the Main Mass of the Complex is in dispute. In a small open pit just south of the Victoria Mine in Dennison Township, it occurs as an inclusion in a younger Contact Sublayer variant.

The younger Contact Sublayer facies are much more common in surface outcrops than the older facies. They are more or less identical in appearance and can be recognized as separate facies only when seen in contact with each other in one outcrop. They are characterized by xenoliths derived from the Footwall of the

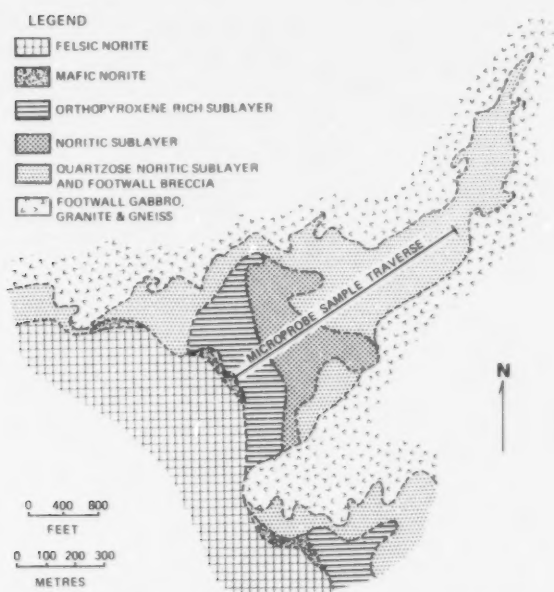


Figure 11.3. Plan of the Whistle Property at the extreme north-eastern corner of the Sudbury Igneous Complex (after Pattison 1979).

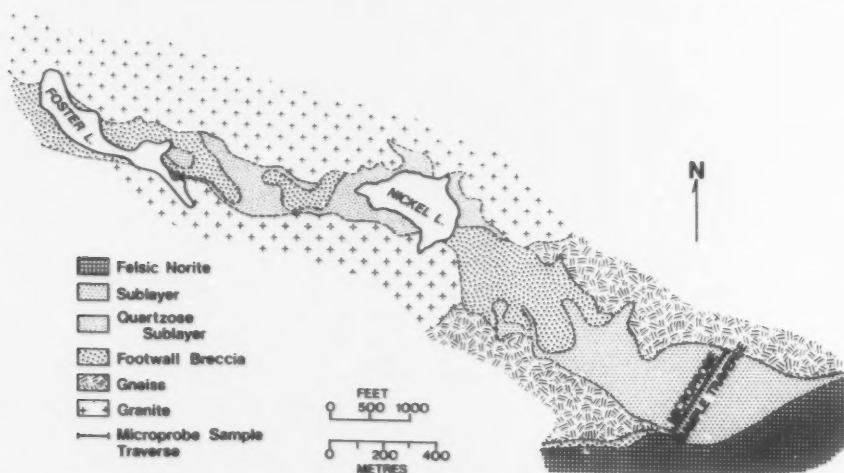


Figure 11.4. Plan of the Foy Offset midway along the North Range (after Pattison 1979).

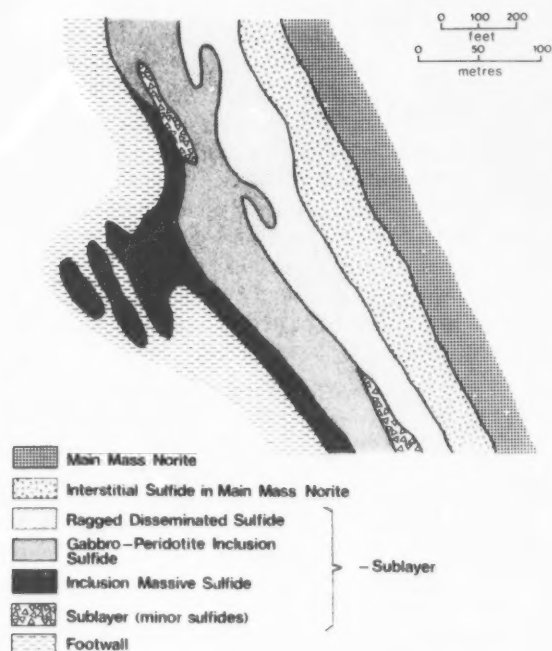


Figure 11.5. Vertical section through the Creighton Mine (after Pattison 1979).

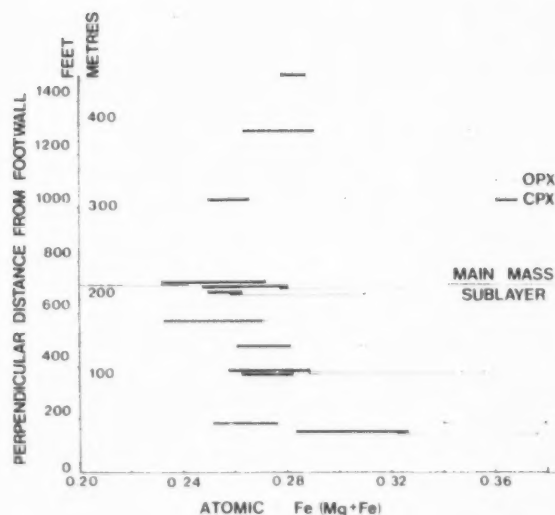


Figure 11.6. Variation in $\text{Fe}/(\text{Fe} + \text{Mg})$ atomic ratio for pyroxenes across phases of the Complex at the Creighton Mine (after Pattison 1979).

Sudbury Igneous Complex. These range from 1 cm to approximately 50 cm in diameter and have subangular to subrounded outlines (Photo 11.2). Along the South Range, fine-grained mafic metavolcanic rocks predominate, and these make up from 50 to just over 90%

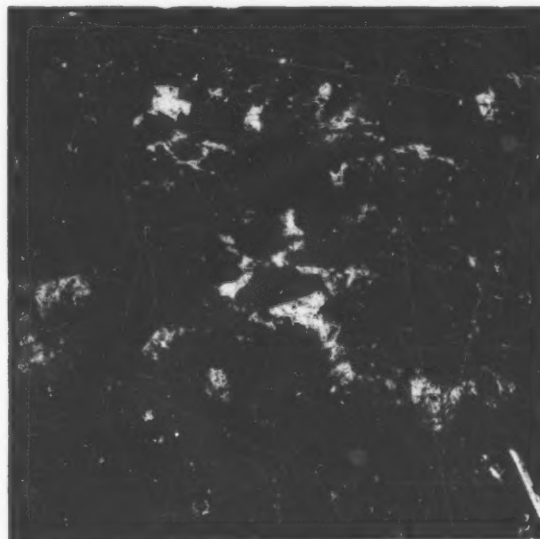


Photo 11.1. Early sulphide-bearing facies of the Contact Sublayer. Coleman Mine Road, Levack Township.



Photo 11.2. Younger facies of the Contact Sublayer. Whistle Property, Norman Township.

of the xenoliths. Huronian metasedimentary xenoliths (5 to 13%) and anorthositic and gabbro-anorthosite xenoliths (1 to 11%) occur only where these rocks are found in the nearby Footwall. Fragments of the Main Mass norite also occur as xenoliths. The younger Contact Sublayer facies, therefore, postdate the Main Mass. This conclusion is substantiated by the intrusive relationships illustrated in Figure 11.7.

One of the authors, Burkhard O. Dressler, has identified zones of inclusion-bearing rocks that cut the marginal Main Mass norite at its base near the Creighton Mine Complex (Photo 11.3). These rocks are very similar in appearance to the younger Contact Sublayer, but differ from them in having a matrix that contains more quartz and has a hornfelsed appearance. These rocks may belong to the Contact Sublayer as Burkhard O. Dressler maintains, or may not be related to it. We have not included them in this discussion. They are, however, shown as Contact Sublayer just east of the

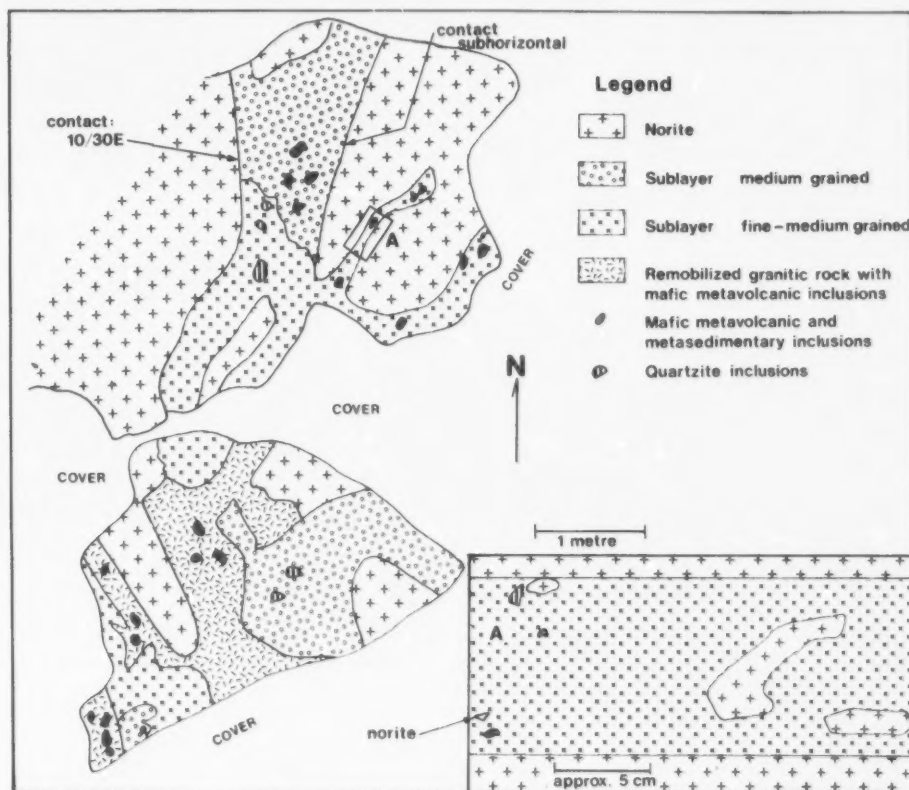


Figure 11.7. Contact Sublayer intruding marginal norite. Outcrop is about 10 m north of the Footwall contact with the Murray Pluton, South Range, McKim Township, 2.15 km north of Highway 144.



Photo 11.3. 'Internal offset'. A facies of the younger Contact Sublayer intruding norite. White fragments are of Huronian arenite. East of Creighton Mine.

Creighton Mine on the geological map, Map 2491 (back pocket).

PETROGRAPHY

In the area where the "xenolithic norite" has been studied most intensively along the North Range between the Strathcona and Fecunis Mines, Naldrett and Kullerud (1967) described it as a fine-grained interser-

tal rock with comparatively fresh pyroxene (hypersthene:augite = 2:1) amounting to 40 to 60 modal %, small tabular grains of plagioclase, and only minor quartz or potassic feldspar (Photo 11.4). The rock name reflects the numerous xenoliths that occur within it. Hewins (1971) described the "Fraser gabbro-norite", found just to the west of the Strathcona Mine, as having an intergranular to subophitic texture, more quartz than the "xenolithic norite", some micrographic intergrowth, and a hypersthene:augite ratio of 1:1. Fewer inclusions are present than at the Strathcona Mine. Still farther to the west, the "Fecunis gabbro" has a similar texture, but is richer in quartz, has a hypersthene:augite ratio of 1:2, and contains very few xenoliths. Hewins (1971) noted that in all of these rocks, the proportion of hypersthene in any sample appears to be related to the proportion of mafic and ultramafic inclusions.

In Figure 11.8, the modal proportions of hypersthene, augite, plagioclase, and quartz in Contact Sublayer rocks from the Strathcona area of the North Range are compared with those of the Main Mass norites and gabbros. It can be seen that the Contact Sublayer rocks are distinctly poorer in quartz than those of the Main Mass. According to Pattison (1979), textures

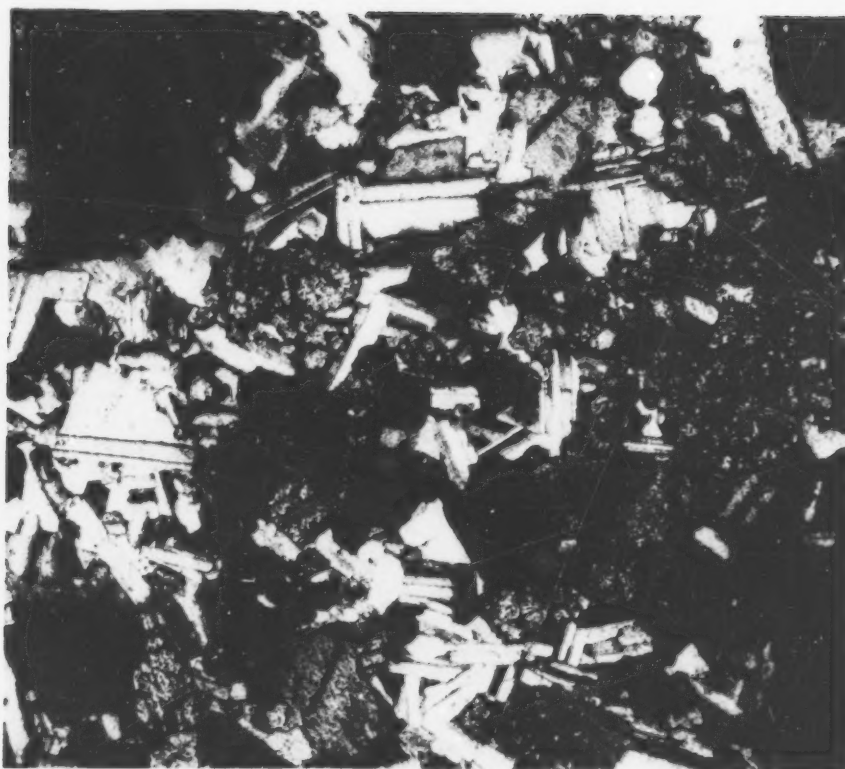


Photo 11.4. Xenolithic norite. Subhedral hypersthene and augite with interstitial, small, subhedral plagioclase laths. Crossed nicols. 100X.

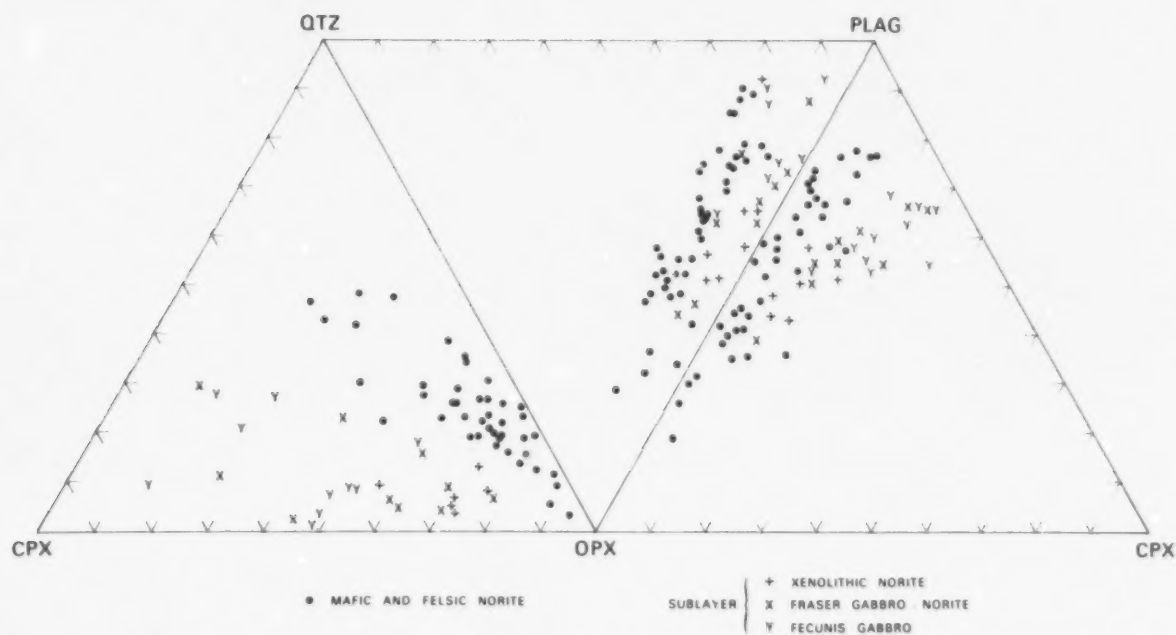


Figure 11.8. Modal proportions of hypersthene, augite, plagioclase, and quartz in Contact Sublayer rocks from the vicinity of the Strathcona Mine compared with proportions in the Main Mass of the Complex (after Naldrett *et al.* 1972).

of Contact Sublayer rocks from elsewhere around the Sudbury Structure are very similar to those described above from the Strathcona-Fecunis area. Nowhere in the Complex has any systematic variation in texture or modal proportion of minerals been observed that is attributable to fractional crystallization.

The "quartz diorite" of the offsets has previously been regarded as a distinctive variant of the Contact Sublayer, carrying more quartz, probable primary in addition to secondary hornblende, plagioclase of a lower than normal anorthite content, and considerable biotite. Pattison (1979) interpreted much of the hornblende as secondary, however, and stated that the contact and Offset Sublayer should be regarded as part of the same magmatic pulse in which differences between the "quartz diorite" and other variants are attributable to deuteric alteration. In general, the authors have no argument with this statement, except that we suggest that some of the quartz within the "quartz diorite" is the result of contamination. This possibility is suggested by Pattison's own data for the North Range at the Whistle and Foy Offsets (*see above*). Contamination may also have resulted in H_2O entering the Contact Sublayer magmas. At the higher pressures associated with the greater depths in the South Range, more H_2O could have dissolved in the magmas, and the stability of hornblende could have been enhanced. This would account for it appearing earlier in the crystallization than was the case on the North Range (and accounting for the primary hornblende that one of the authors (A.J. Naldrett), still believes characterizes much of the "quartz diorite").

MINERAL COMPOSITIONS

No systematic variation in mineral composition of the Contact Sublayer consistent with gravitational differentiation has been noted. Some interesting variation in compositions of minerals have been documented, however, through masses of Contact Sublayer as discussed below.

Pyroxenes

Hewins (1971) noted that at the Fecunis and Fraser Mines, the pyroxenes have constant, relatively Fe-rich compositions in the central parts of Contact Sublayer masses, but become more magnesian at the upper and lower boundaries (*see* Figure 11.9). Hewins found that xenocrysts of Mg-rich pyroxene were present at the margins, and he observed that where this was so, the pyroxenes that had grown in place were more magnesian than the norm. Hewins concluded that the Contact Sublayer magma was contaminated at its margins in the direction of decreasing $Fe/(Fe + Mg)$ ratio. Noting that in most cases, the contaminated margins were adjacent to mafic norite, and that the mafic norite was the

only country rock close to the Contact Sublayer with pyroxenes magnesian enough to supply the xenocrysts, he attributed the variation to contamination of Contact Sublayer by mafic norite. He observed also that Cr_2O_3 is highest in samples of Fecunis Sublayer that, on the basis of its $Fe/(Fe + Mg)$ ratio, appear to be most contaminated. This relationship is consistent with the mafic norite being the source of the contamination, because it is the only rock in the vicinity of the Contact Sublayer with pyroxenes richer in Cr_2O_3 than those of the Contact Sublayer. These observations lead Hewins to conclude that the Contact Sublayer was younger than the Main Mass of the Complex.

Schuyler (1984) has proposed an alternative interpretation (regarded as viable by R.H. Hewins), that the sample studied by Hewins (1971) and shown in Figure 11.9 as the uppermost of the Contact Sublayer at Fecunis is in fact an inclusion-rich, basal facies of the mafic norite. This would remove one of the principle arguments in favour of a younger age for the Contact Sublayer.

Pattison (1979) found a marked and progressive increase in the $Fe/(Fe + Mg)$ ratio of pyroxenes along the Sublayer protrusion at the Whistle Property, away from the Main Mass of the Complex into the Footwall (*see* Figure 11.3 for line of section). This variation is illustrated in Figure 11.10, where it is seen that it is accompanied by an increase in the zoning shown by the

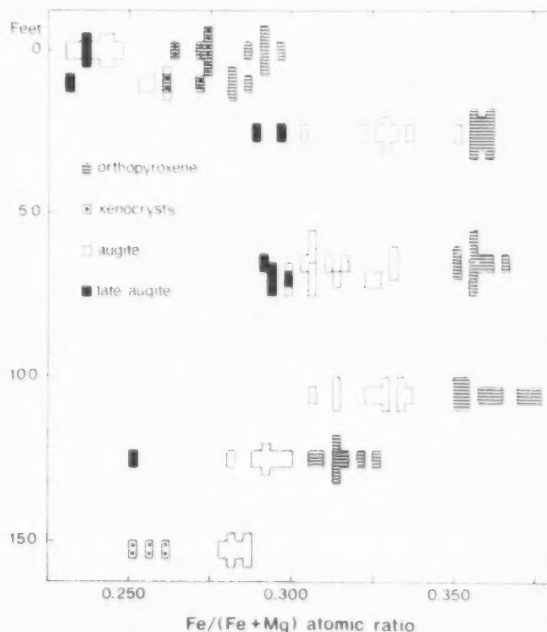


Figure 11.9. $Fe/(Fe + Mg)$ variation in pyroxene along a profile through the Contact Sublayer and flanking rocks at the Fecunis Mine (after Hewins 1971).

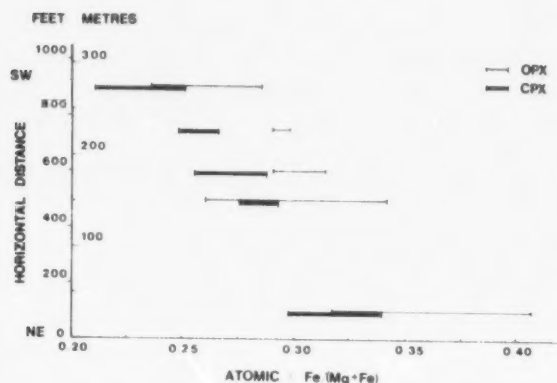


Figure 11.10. Fe/(Fe + Mg) variation in pyroxene along a profile through the Contact Sublayer at the Whistle Property. See Figure 11.3 for the location of the profile. Note that the uppermost sample is not of Contact Sublayer but is of inclusion-rich facies of the mafic norite. The third sample from the top contains olivine within its matrix (the only occurrence observed at Sudbury). The olivine has a composition that is in equilibrium with the ortho- and clinopyroxenes in the sample. The strong Fe-enrichment observed toward the contact in the samples beneath this is paralleled by a marked increase in their modal quartz content (after Pattison 1979).

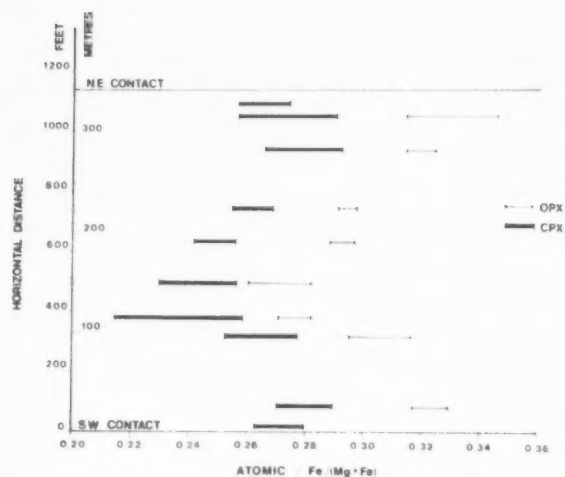


Figure 11.11. Fe/(Fe + Mg) variation in pyroxene along a profile perpendicular to the Foy Offset. See Figure 11.4 for the location of the profile (after Pattison 1979).

pyroxenes. Rather similar variation is present along a traverse perpendicular to the Foy Offset (see Figure 11.4 for line of traverse), where the marginal rocks are clearly enriched in Fe over those at the core of the structure (Figure 11.11). At both the Whistle Property and the Foy Offset, the Fe-enrichment is accompanied by an increase in quartz (from olivine-bearing to quartz-rich Contact Sublayer in the case of the Whistle Property), and thus resembles the trends that have been documented for the Main Mass quartz-rich norite of the South Range.

Plagioclase

Plagioclase grains are zoned from An_{66} (cores) to An_{50} (rims) in the "Fecunis gabbro", from An_{35} (cores) to An_{32} (rims) in the "Fraser gabbro-norite", and from An_{69} to An_{57} at the Strathcona Mine. The extent of this zoning is sufficient to mask any other compositional trends or variations that might be present.

Oxide Minerals

Hewins (1971) presented data on the compositions of magnetite and ilmenite. Most magnetite grains contain exsolved ilmenite lamellae and no attempt was made to estimate the proportions of these and recalculate the composition of the original titaniferous magnetite. Disregarding the ilmenite, which would hold very little Cr_2O_3 , magnetites from the "Fraser gabbro-norite" contained 2 to 5 wt% Cr_2O_3 , those from the "Fecunis gabbro" 0 to 2%, and those from the "xenolithic norite" up to 7 wt% (this last data from Greenman 1970).

GEOCHEMISTRY

The textures of the Contact Sublayer rocks indicate that they are not cumulates, but are largely the result of *in situ* crystallization, and therefore, provide insight into the composition of the magmas that gave rise to them. Consequently, their bulk chemical compositions are of particular interest. Chemical data of selected Contact Sublayer samples from the North and South Ranges have been obtained by Rao *et al.* (1983) and some of their analyses are presented in Tables 11.1 and 11.2.

Major Elements

The mineralogical variations of the Contact Sublayer rocks are reflected in their normative mineral compositions. All of the samples studied by Rao *et al.* (1983) are silica oversaturated. Normative quartz varies from about 1 to as much as 20 and hypersthene from 14 to 30 (norms are in wt%).

Harker (SiO_2 variation) diagrams are presented in Figure 11.12. The use of SiO_2 as a measure of a compositional variation in the samples, which is partly the result of differentiation, is supported by its correlation with the Differentiation Index (D.I.). There are no smooth variations of major oxides with SiO_2 , but K_2O correlates significantly and positively with SiO_2 , suggesting that K is acting as an incompatible element. Both MgO and FeO (total) show a strong negative correlation with SiO_2 ; Na_2O and Al_2O_3 exhibit a weak negative correlation with SiO_2 , but there is a moderately strong correlation between them, reflecting their mutual occurrence in plagioclase. A marked clustering of samples is apparent; samples from the North Range fall in 2 areas, while those from the South Range plot between them.

TABLE 11.1: MAJOR ELEMENT ANALYSES OF SUBLAYER SAMPLES (RECALCULATED TO 100 ON H₂O-FREE BASIS).

NORTH RANGE														
SAMPLE NUMBER	BVR-1	BVR-2	BVR-3	BVR-4	BVR-5	BVR-6	BVR-7	BVR-8	BVR-9	BVR-10	BVR-11	BVR-20	MEAN	STANDARD DEVIATION
SiO ₂	62.93	52.87	52.92	62.00	63.11	52.48	61.44	60.39	63.42	61.76	51.66	59.49	58.74	5.0
TiO ₂	0.93	1.20	1.32	0.75	0.92	1.30	0.50	0.78	0.97	0.81	1.31	1.08	1.01	0.22
Al ₂ O ₃	14.90	15.51	13.71	14.73	14.55	14.50	15.26	12.68	14.59	15.25	14.67	15.39	14.63	0.71
FeO*	6.90	11.11	12.61	9.14	8.41	12.67	7.60	8.94	7.06	8.16	12.84	8.73	9.51	2.16
MnO	0.11	0.16	0.18	0.13	0.13	0.19	0.11	0.17	0.11	0.18	0.17	0.14	0.15	0.19
MgO	3.71	6.18	6.79	3.69	3.95	6.04	3.81	8.37	3.91	4.07	6.21	4.07	5.08	1.56
CaO	4.59	8.66	8.76	4.58	2.73	8.41	5.25	4.94	5.15	3.15	9.52	5.93	5.96	2.24
Na ₂ O	2.96	3.15	2.35	2.73	3.00	2.76	3.17	1.83	2.41	3.42	2.81	3.23	2.83	0.41
K ₂ O	2.28	1.16	1.16	2.25	3.20	1.56	2.56	1.90	2.39	3.20	0.81	1.98	2.03	0.76
MgNo	0.49	0.60	0.49	0.42	0.46	0.46	0.47	0.63	0.50	0.47	0.47	0.45	—	—
DI	58.30	34.50	31.40	55.47	61.60	34.10	56.00	42.30	55.10	60.80	29.40	51.50	—	—
CIPW Norm														
qz	19.70	1.30	3.30	19.20	17.50	1.70	14.30	15.70	20.80	13.00	1.10	12.00	—	—
hy	14.40	20.10	22.70	16.00	18.70	21.30	14.30	30.00	15.80	18.10	21.00	15.00	—	—

SOUTH RANGE														
SAMPLE NUMBER	BVR13	BVR14	BVR15	BVR16	BVR17	BVR18	BVR19	BVR12	BVR21	BVR22	BVR23	MEAN	STANDARD DEVIATION	
SiO ₂	54.45	58.96	59.78	58.81	57.43	58.78	56.38	57.72	56.75	53.91	58.87	57.43	1.84	
TiO ₂	1.07	0.99	0.85	1.09	0.80	0.88	0.79	0.55	1.60	1.49	0.80	0.99	0.31	
Al ₂ O ₃	17.81	15.36	15.17	15.74	16.87	12.95	15.54	16.19	15.87	17.93	16.44	15.93	1.32	
FeO*	8.80	8.92	7.77	8.86	9.01	10.14	9.50	8.48	9.74	11.50	7.68	9.13	1.13	
MnO	0.14	0.13	0.12	0.14	0.13	0.15	0.11	0.10	0.14	0.13	0.12	0.13	0.01	
MgO	5.76	4.93	5.99	4.13	5.02	5.76	5.71	6.54	5.37	3.81	5.13	5.28	0.80	
CaO	8.09	5.91	5.84	6.51	5.54	7.27	6.09	6.40	6.36	6.48	6.75	6.48	0.71	
Na ₂ O	3.22	2.68	2.90	2.99	2.71	2.47	3.77	2.79	2.96	3.37	2.50	2.95	0.43	
K ₂ O	1.25	2.10	1.58	1.73	2.49	1.61	2.11	1.23	1.21	1.37	1.36	1.67	0.42	
MgNo	0.54	0.50	0.58	0.45	0.50	0.50	0.52	0.58	0.50	0.37	0.54	—	—	
DI	37.20	47.50	45.80	47.60	45.31	42.60	45.80	44.00	—	41.60	44.00	—	—	
CIPW norm														
qz	2.70	12.70	12.10	12.30	7.90	12.60	16.80	—	13.00	5.20	13.00	—	—	
hy	20.40	18.80	22.80	16.80	23.30	19.00	17.60	—	19.50	19.60	19.50	—	—	

* Total iron as FeO

MgNo = MgO/(MgO + FeO) in atomic proportion

DI is the Differentiation Index

The Contact Sublayer rocks are rich in K₂O and SiO₂ compared to continental tholeiitic basalts of similar MgO content. When plotted on an (Na₂O + K₂O) versus SiO₂ diagram, they plot in the tholeiitic and high-alumina fields of Kuno (1968: Figure 11.13). On an AFM diagram (Figure 11.14), their compositions spread out over the calc-alkalic field of Irvine and Baragar (1971) with no discernable trend.

Trace Elements

In the Contact Sublayer rocks, compatible trace elements such as Sc, Co, and Cr generally decrease with increasing SiO₂, although the trends are not smooth. The incompatible trace elements, Th, Hf, Zr, La, and Rb all show strong to moderate correlations with K₂O and SiO₂ ($r = 0.5$ to 0.8 ; Figure 11.15), and Zr, Th, and Hf have significant correlations amongst them-

selves. Sr correlates positively with CaO and antipathetically with SiO₂.

Rare Earth Elements (REE)

REE patterns for the Contact Sublayer samples are illustrated in Figure 11.16. The Contact Sublayer gabbro-norites have very high total REE contents ranging from 93 to 206 ppm (see Table 11.2). Their chondrite-normalized (Haskin *et al.* 1968) patterns display distinct LREE enrichment, no fractionation of HREE, and no significant Eu anomalies. The REE patterns for North and South Ranges are very similar, although the North Range rocks are characterized by higher La/Yb ratios than those of the South Range, as is seen in Figure 11.17. There is also a close resemblance between REE patterns of the Contact Sublayer and those of the marginal norites of the overlying Main Mass of the Complex (Figure 11.18). Kuo and Crocket (1979)

CHAPTER 11

TABLE 11.2: TRACE ELEMENT ANALYSES OF SUBLAYER SAMPLES (values are in ppm).

SAMPLE NUMBER	NORTH RANGE												STANDARD DEVIATION
	BVR-1	BVR-2	BVR-3	BVR-4	BVR-5	BVR-6	BVR-7	BVR-8	BVR-9	BVR10	BVR11	BVR20	MEAN
La	33.80	27.24	28.24	34.76	32.70	32.0	38.25	27.12	38.12	34.72	17.96	43.50	32.37
Ce	72.40	68.30	66.00	88.20	67.00	70.80	97.83	55.40	94.40	72.50	48.20	84.14	73.76
Nd	28.40	24.90	27.80	39.40	26.90	38.90	21.72	21.10	33.00	29.20	17.83	34.20	28.61
Sm	5.50	5.52	6.36	5.26	4.50	7.31	5.57	4.28	6.03	4.90	4.65	5.92	5.49
Eu	1.60	1.73	1.81	0.99	1.05	1.93	1.48	1.25	1.51	1.52	1.96	1.51	1.57
Tb	0.65	0.71	0.77	0.74	0.52	0.67	0.73	0.50	0.46	0.53	0.76	0.67	0.64
Yb	1.84	1.41	2.05	2.42	1.58	2.57	1.70	1.32	2.13	1.74	1.43	1.50	1.80
Lu	0.32	0.18	0.35	0.43	0.27	0.41	0.18	0.25	0.28	0.27	0.27	0.26	0.29
REE	144.5	130.0	133.4	172.2	134.5	154.6	167.5	111.2	175.9	145.4	91.1	171.7	144.5
Th	5.7	1.7	2.0	5.5	6.5	2.0	6.0	4.3	6.3	6.3	1.1	4.8	4.3
Hf	2.9	1.8	1.3	4.6	6.1	1.9	3.3	3.0	5.0	2.4	1.5	4.1	3.4
Ta	0.44	0.10	0.18	0.43	0.43	0.17	0.30	0.35	0.40	0.40	0.18	0.32	0.31
Ba	1000	650	550	700	990	640	730	540	800	1000	—	1000	800
Sc	18	29	36	17	15	31	18	19	19	17	34	21	22.6
Co	24	39	55	19	19	47	32	51	27	25	59	35	36
Cr	138	193	228	117	117	163	138	370	162	116	146	126	—
Zr	148	88	85	152	173	76	167	123	200	166	52	188	134
Y	20	14	22	19	18	23	19	16	19	20	17	20	19
Sr	420	580	456	387	263	477	398	288	379	281	602	496	419
Rb	48	24	28	45	65	43	70	68	55	146	21	36	54
RATIOS													
La/Yb	18.37	19.32	13.77	14.36	20.69	12.45	22.50	20.54	17.90	19.95	12.55	29.0	—
Zr/Y	7.4	6.28	3.85	9.61	9.60	3.30	7.67	7.69	10.50	8.30	3.01	9.40	—
Rb/Sr	0.114	0.04	0.06	0.12	0.25	0.09	0.18	0.24	0.14	0.52	0.03	0.07	—
Y/Sr	0.05	0.024	0.048	0.049	0.068	0.048	0.048	0.055	0.050	0.070	0.028	0.040	—
Zr/Hf	51.60	48.09	65.40	31.45	28.40	40.86	50.60	41.00	40.00	69.10	33.70	45.80	—
Th/Hf	1.98	0.93	1.54	1.61	1.41	0.86	1.82	1.40	1.26	2.60	0.71	1.17	—
SAMPLE NUMBER	SOUTH RANGE												STANDARD DEVIATION
	BVR12	BVR13	BVR14	BVR15	BVR16	BVR17	BVR18	BVR19	BVR21	BVR22	BVR23	MEAN	
La	20.30	18.90	29.35	27.65	34.72	24.98	25.30	36.10	43.30	37.30	30.40	29.51	7.24
Ce	46.50	49.50	64.00	74.10	91.60	54.70	65.80	99.80	93.00	78.30	69.50	71.54	17.93
Nd	25.70	21.72	22.47	23.50	25.00	17.43	22.40	28.20	54.80	30.50	43.90	28.69	11.04
Sm	3.36	4.63	5.01	4.83	6.14	4.46	4.54	6.30	8.16	6.14	5.00	5.32	1.28
Eu	1.16	1.50	1.46	1.18	1.55	1.37	1.08	2.02	2.40	2.64	1.02	—	4.74
Tb	0.58	0.57	0.38	0.64	0.65	0.47	0.91	1.44	0.86	1.03	0.47	—	—
Yb	1.09	1.99	1.83	2.13	2.30	1.93	2.10	2.45	3.77	3.42	1.89	2.26	0.75
Lu	0.18	0.30	0.35	0.24	0.34	0.24	0.37	0.42	0.55	0.57	0.32	—	—
REE	98.87	99.11	124.85	134.30	162.30	105.60	122.50	176.70	206.80	159.90	152.50	—	—
Th	5.1	2.0	5.0	3.8	4.4	4.0	2.5	5.9	3.0	1.5	4.8	3.76	1.42
Hf	3.5	3.4	3.6	3.0	3.0	2.2	3.2	6.8	2.3	2.2	3.4	3.32	1.27
Ta	0.65	0.31	0.45	0.34	0.40	0.38	0.31	0.71	0.65	0.64	0.34	0.46	0.16
Ba	480	635	610	640	784	490	600	635	820	685	—	—	150
Sc	19	25	23	20	24	23	25	33	25	27	19	24	4.01
Co	26	34	34	38	30	35	40	44	37	38	30	35	5.11
Cr	430	230	217	400	198	290	242	153	220	152	110	—	—
Zr	139	145	150	107	132	94	117	170	149	168	109	134	25.14
Y	16	19	23	19	21	19	20	29	34	35	22	23.4	6.4
Sr	466	484	323	427	418	425	356	315	388	393	428	402	54
Rb	34	43	67	54	57	143	50	76	44	41	56	60.5	29.90
RATIOS													
La/Yb	18.6	9.50	16.04	12.98	15.10	12.94	12.05	13.18	11.48	10.90	16.10	—	—
Zr/Y	8.69	7.60	6.50	5.60	6.28	4.95	5.85	5.86	4.38	4.80	4.95	—	—
Rb/Sr	0.07	0.09	0.21	0.13	0.14	0.34	0.14	0.24	0.11	0.10	0.13	—	—
Y/Sr	0.034	0.04	0.07	0.044	0.05	0.045	0.056	0.09	0.087	0.089	0.05	—	—
Zr/Hf	39.70	42.40	41.70	35.40	43.56	42.70	36.30	25.0	63.90	74.70	32.06	—	—
Th/Hf	1.46	0.58	1.34	1.26	1.45	1.82	0.77	0.86	1.30	0.66	1.41	—	—

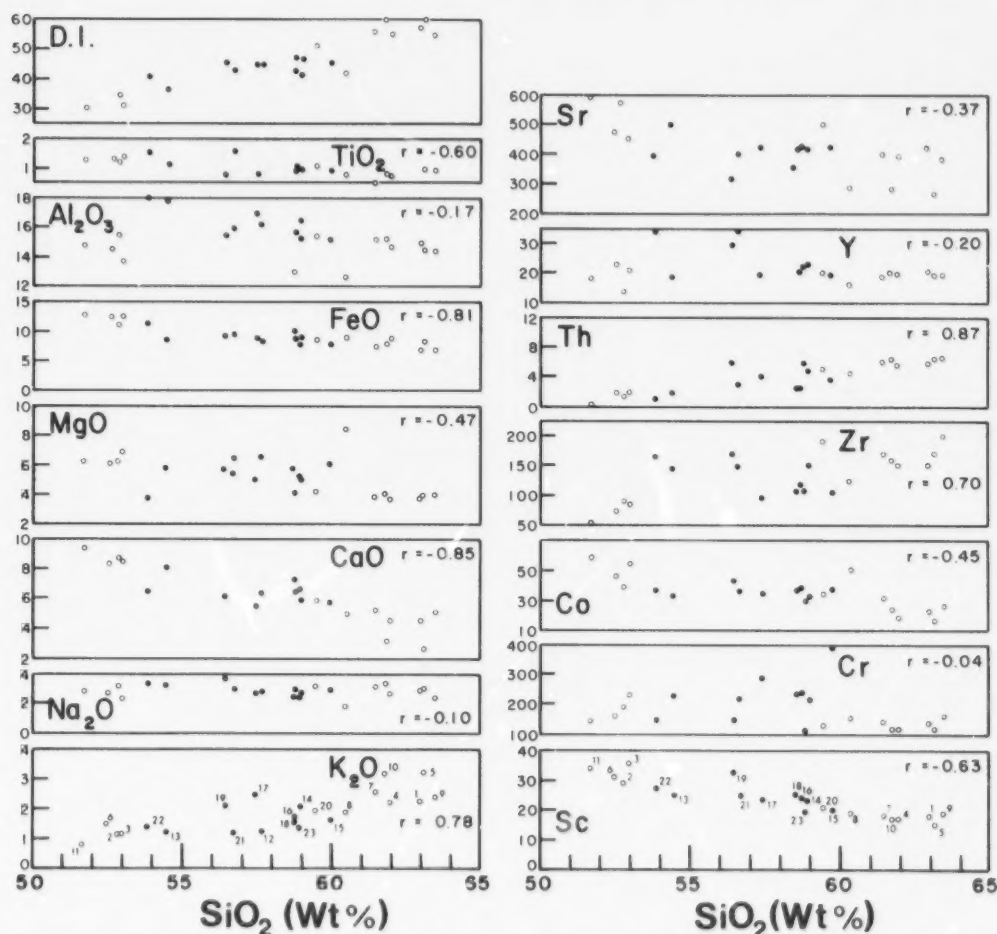


Figure 11.12. A. Plot of SiO_2 versus major oxides (on an anhydrous basis). The correlation coefficients (r) are also shown. Open circles = North Range; closed circles = South Range. B. SiO_2 versus Sc, Co, Cr, Zr, Th, Y, and Sr plots. Symbols are the same as in A. Correlation coefficients are also shown. Numbers refer to sample numbers in Table 11.3.

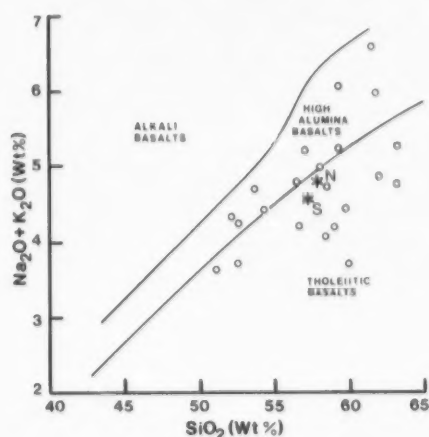


Figure 11.13. SiO_2 versus ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) plot (anhydrous). N and S (shown as stars) refer to the mean compositions of the North and South Range Contact Sublayer rocks, respectively.

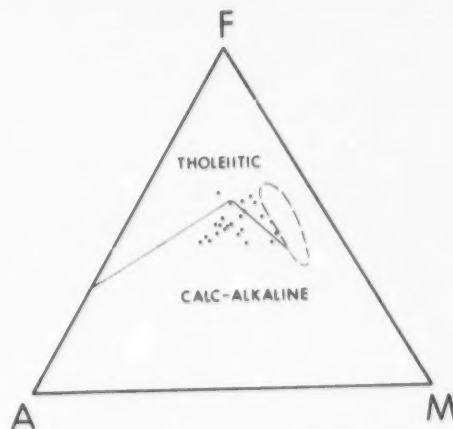


Figure 11.14. AFM diagram for the Contact Sublayer samples. The solid line separates the tholeiitic and calc-alkalic fields of Irvine and Baragar (1970). The field (dashed line) for gabbros and norites of the Wanapitei intrusion of the Sudbury district (Finn *et al.* 1968) is indicated for comparison.

considered these norites to represent the parental magma of the Complex as a whole.

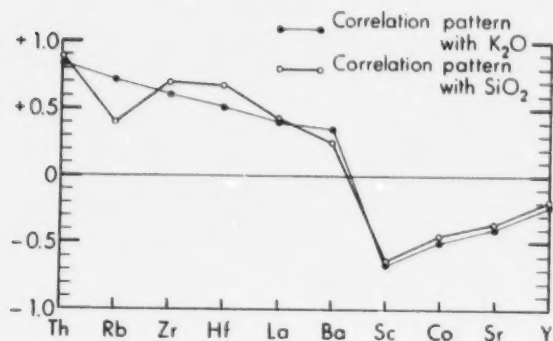


Figure 11.15. Correlation of certain trace elements with SiO_2 and K_2O .

Geochronology

Gibbins and McNutt (1975: *see* Figure 10.12) reported an $\text{Sr}^{87}/\text{Sr}^{86}$ age of 1957 Ma and an $(\text{Sr}^{87}/\text{Sr}^{86})$ ratio of 0.7055 ± 0.0012 for 5 samples of Contact Sublayer from the South Range, as compared to an age of 1957 Ma and a ratio of 0.7063 for the Main Mass of the norite. Neither the age nor the ratio are significantly different, although Pattison (Geologist, Inco Metals Limited, personal communication, 1983) reported that some confusion exists as to whether Gibbins and McNutt's samples were collected from undisputed Contact Sublayer or from the overlying quartz-rich norite of the Main Mass of the Complex.

Discussion

The major and compatible trace element (Co, Cr, Sc, and Sr) trends described above are broadly indicative of fractional crystallization of pyroxene and pla-

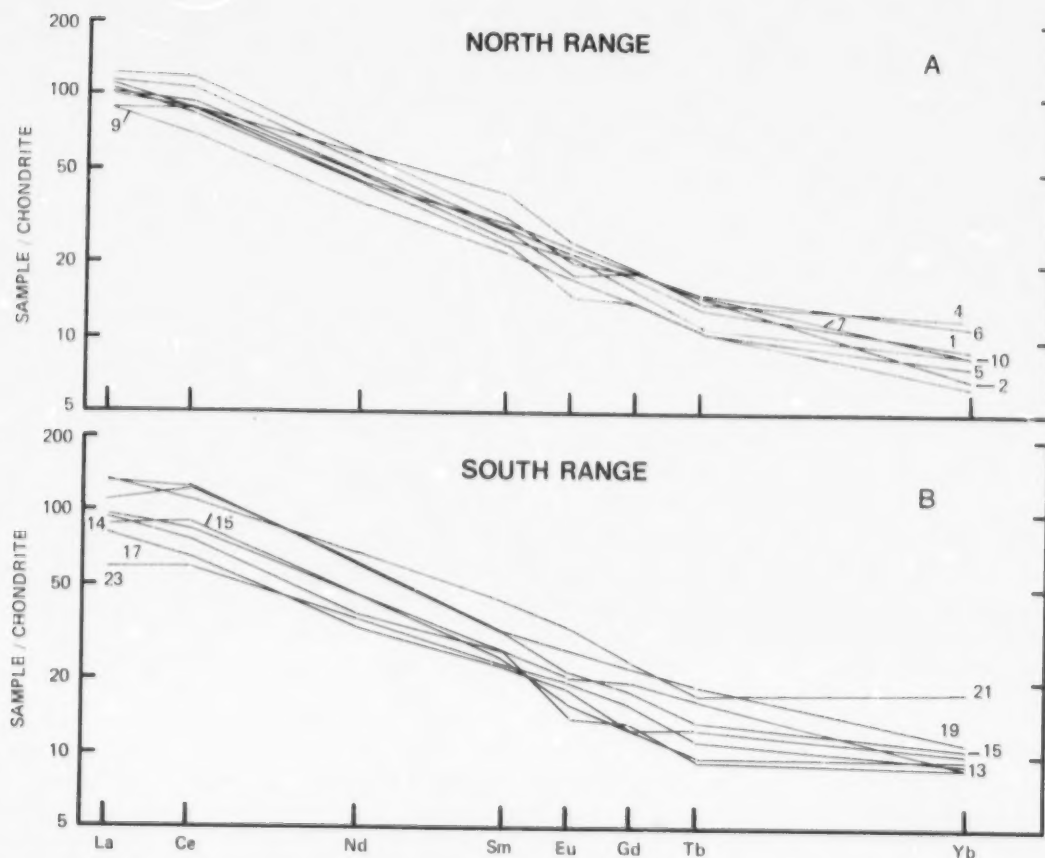


Figure 11.16. Chondrite-normalized rare earth element patterns for Contact Sublayer samples from the North and South Ranges. Numbers indicated for each pattern refer to the sample numbers in Table 11.2 (with the prefix BVR omitted).

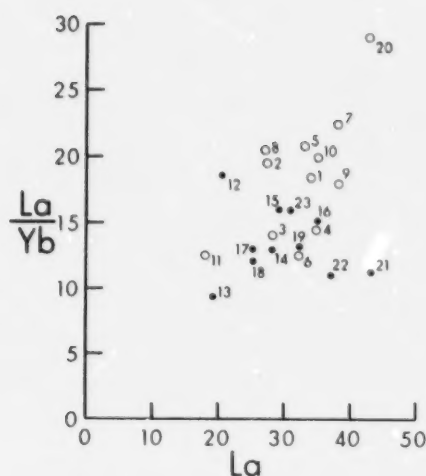


Figure 11.17. La/Yb versus La plot. Open circles = North Range; closed circles = South Range. The numbers refer to sample numbers in Table 11.2 (prefix BVR omitted).

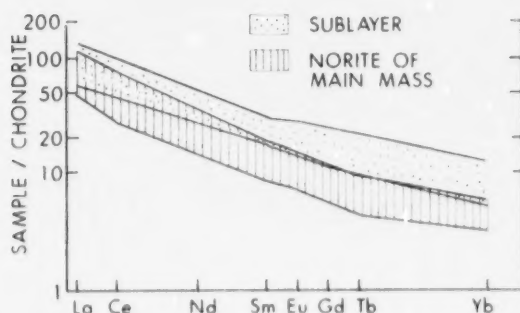


Figure 11.18. The range of chondrite-normalized rare earth element patterns obtained in this study (Figure 11.15) for the Contact Sublayer (stippled dots) compared with those obtained by Kuo and Crocket (1979) for the Main Mass norites (vertical shading).

gioclase, although the lack of smooth trends suggest that the rocks are not products of a single fractionating liquid. The abundances and within-suite variations of the incompatible elements, including the LREE enrichment, are not, however, explicable in terms of a simple fractionation model.

In view of Watson's (1982) recent experimental data relating to basalt contamination, the observed K₂O and SiO₂ variation may be attributed to the result of extensive bulk assimilation of crustal rocks by Contact Sublayer magma. The Th, Hf, and Ta data on the Sublayer rocks (see Wood 1980, for the utilization of Th, Hf, and Ta to establish the nature and extent of the crustal contamination of magmas) also support a contamination model.

Assimilation of crustal rocks by non-superheated liquids may be accompanied by crystallization. It is unlikely that latent heat of crystallization will be transformed with 100% efficiency into heat of melting, so

that crystallization will exceed melting, probably by a considerable amount, and the effects of crystallization of a magma on the major and compatible trace element spectrum will exceed those of assimilation. It is with the incompatible trace elements that assimilation is likely to make its mark. In the case of ratios of incompatible to compatible trace elements, the effect of crystallization plus assimilation will be much more marked than that of assimilation alone. Rao *et al.* using the equations of DePaolo (1981) provide a reasonable explanation for the compositional variations of the Sudbury Contact Sublayer.

INCLUSIONS IN THE SUBLAYER

Inclusions (xenoliths) in the Contact Sublayer can be derived into 2 main groups, those of obviously local derivation (felsic gneiss, quartzites, amphibolites) and those composed of mafic and ultramafic rocks, many of which do not outcrop in the Sudbury area. This section is concerned with the latter group.

Mafic and ultramafic inclusions within the Contact Sublayer at the Strathcona Mine were first briefly described by Vos and Moorhouse (1965); Souch. Podolsky *et al.* (1969) noted their widespread occurrence around the margin of the Complex. Naldrett and Kullerud (1967) analyzed olivine and pyroxenes in inclusions from the Strathcona Mine, and found a positive correlation between their Fe content and the proportion of felsic minerals in the samples. Naldrett and Kullerud suggested that the inclusions were derived from a cryptically layered ultramafic to mafic hidden zone of the Complex. Greenman (1970) also examined inclusions in the vicinity of the Strathcona Mine. He noted that the olivine-free inclusions are highly recrystallized with clinopyroxene: orthopyroxene modal ratios of about 3:1, and he showed that the olivine-bearing inclusions appear concentrated toward the base of the Contact Sublayer. Rae (1975) studied a systematically collected suite of inclusions from the Strathcona Mine, and Scribbins (1978) studied samples judged to be representative of the South Range from the collection of Inco Metals Limited. The following descriptions are based on these 2 studies, published by Scribbins *et al.* (1984).

Petrography

The inclusions range in diameter from a few mm (Hewins 1971) to several m. Typical examples examined in the Copper Cliff South, Creighton, and Strathcona Mines are from 8 cm to 1.5 m and have subrounded shapes, in contrast to the more angular nature of Footwall inclusions.

The totals and percentages of the various rock types examined by Scribbins *et al.* (1984) from the South Range and the Strathcona Mine on the North

TABLE 11.3: ROCK TYPES FOUND AS INCLUSIONS IN THE SUBLAYER AT SUDBURY.

	SOUTH RANGE		STRATHCONA	
	TOTAL	%	TOTAL	%
Orthopyroxenite	4	4.6	7	2.9
Olivine Orthopyroxenite	5	5.7	2	0.8
Harzburgite	36	40.8	15	6.3
Clinopyroxenite	2	2.3	8	3.4
Olivine Clinopyroxenite	0	0	8	3.4
Wehrlite	0	0	17	7.1
Websterite	0	0	14	5.9
Olivine Pyroxenite	0	0	6	2.5
Lherzolite	0	0	8	3.4
Dunite	0	0	1	0.4
Olivine Norite	1	1.1	1	0.4
Olivine Melanorite	2	2.3	15	6.3
Olivine Melatroctolite	2	2.3	0	0
Melatroctolite	0	0	7	2.9
Leuco Norite	1	1.1	1	0.4
Norite	2	2.3	2	0.8
Melanorite	10	11.3	47	19.8
Augite Norite	2	2.3	0	0
Augite Melanorite	13	14.7	46	19.4
Gabbro	0	0	1	0.4
Melagabbro	0	0	1	0.4
Hypersthene Gabbro	4	4.6	1	0.4
Hypersthene Melagabbro	4	4.6	30	12.7
	88	100.0%	238	100.0%

Range are summarized in Table 11.3. A noticeable feature is the almost complete absence of clinopyroxene-dominant rock types such as clinopyroxenite, wehrlite, websterite, and lherzolite among the South Range inclusions.

Petrographic descriptions of the 5 most common rock types are summarized in Table 11.4. Cumulus textures (Wager *et al.* 1960) are common. Most of the harzburgites, olivine melatroctolites, and olivine orthopyroxenites have cumulus olivine poikilitically enclosed by orthopyroxene and plagioclase (Photo 11.5). Some of the olivine-rich harzburgites can be interpreted as mesocumulates with orthopyroxene and plagioclase interstitial to large olivine grains. The wehrlites and olivine clinopyroxenites are mesocumulates with optically zoned orthopyroxene and plagioclase interstitial to olivine and clinopyroxene. The websterites are meso- to adcumulates; the norites and gabbros are meso- to orthocumulates (Photo 11.6) with cumulus pyroxene and intercumulus plagioclase, although occasionally cumulus plagioclase is present. Some harzburgite samples have subrounded, resorbed olivine grains poikilitically enclosed by orthopyroxene, and coronas of orthopyroxene surrounding olivine grains within plagioclase are also common (Photo 11.7).

Recrystallization of varying intensity is common to many of the inclusions and is attributed to the heating effect of the Contact Sublayer magma. The South

Range xenoliths generally show more recrystallization and alteration than those from the Strathcona Mine.

Mineral Compositions

Olivine compositions in the xenoliths range from $Fo_{74.4}$ to $Fo_{85.6}$ for the South Range, and from $Fo_{72.8}$ to Fo_{85} for the Strathcona inclusions (Scribbins *et al.* 1984; Naldrett and Kullerud 1967). In Figure 11.19, olivine compositions are plotted against the modal percentage of plagioclase in the rock. The more forsteritic olivines tend to occur in the more mafic rocks, although this relationship is not apparent in the South Range inclusions by themselves because plagioclase-bearing ultramafic rocks are not represented there.

Orthopyroxene and clinopyroxene compositions are plotted in the pyroxene quadrilateral in Figures 11.20a and 11.20b. The fields of pyroxene compositions for the Strathcona Mine (North Range) and South Range inclusions are similar, although the South Range orthopyroxenes show a greater variation in Mg:Fe ratio and Ca content than those from the Strathcona Mine. The orthopyroxene is bronzite and ranges from $Fs_{11.5}$ to Fs_{31} ; the clinopyroxene generally varies from augite to salite. Orthopyroxene in ultramafic inclusions, as would be expected, has higher Mg:Fe ratios than that in mafic inclusions.

Plagioclase ranges from $An_{80.6}$ to $An_{20.7}$ in the South Range inclusions; from $An_{78.1}$ to An_{11} in the Strathcona inclusions. The more anorthitic plagioclase occurs interstitially in olivine melatroctolite ($An_{80.5}$), harzburgite ($An_{87.4}$), and as cumulus grains in norite ($An_{80.6}$).

Chromite has been analyzed in 1 orthopyroxenite and 8 harzburgite inclusions from the South Range. The Cr_2O_3 contents range from 31.2 to 50.4 wt%, similar to that of chromite from the Strathcona inclusions which range up to 50.8 wt% Cr_2O_3 . Partitioning of Fe between Fe^{3+} and Fe^{2+} was accomplished for chromite using the expression: $(Fe_{tot} + Mg + Mn) - (2Ti + 1/2Al + 1/2Cr) = 3/2Fe^{3+}$. As seen in Figure 11.21, the compositional fields of the chromite are typical of those from layered intrusions.

Source of the Inclusions

Three possible sources can be suggested for the Contact Sublayer inclusions:

1. the mantle
2. a mafic to ultramafic body older than the Sudbury Igneous Complex
3. a hidden layered sequence beneath, but genetically-related to the Complex

A mantle origin for the inclusions is unlikely for several reasons:

TABLE 11.4: PETROGRAPHY OF MAJOR INCLUSION ROCK TYPES.

ROCK TYPE	MINERALS PRESENT	APPROXIMATE MODE %	APPROXIMATE GRAIN SIZE	CHARACTERISTICS
Harzburgite	Olivine	45-75%	Up to 2 mm (rarely to 6 mm)	Anhedral, subequant; also as subrounded; resorbed grains 0.2 to 1 mm poikilitically enclosed within orthopyroxene and plagioclase.
	Orthopyroxene	15-50%	1 to 3 mm	Tabular; coronas of orthopyroxene in places surround olivine enclosed in plagioclase.
	Plagioclase	5-10%	<0.5 mm	Interstitial; antithetic relationship between olivine size and plagioclase abundance.
	Clinopyroxene	0-5%	0.5 to 1 mm	Ragged, interstitial grains.
Wehrlite	Olivine	45-60%	Up to 10 mm	Large equant to elongate anhedral grains; also as spherical, resorbed grains 0.1 to 0.2 mm poikilitically enclosed within orthopyroxene and plagioclase.
	Clinopyroxene	30-50%	<3 mm	Smaller and more variable in size than olivine; simple twinning common to large grains.
	Plagioclase	<10%	<0.5 mm	Interstitial.
	Orthopyroxene	<5%	0.2 to 0.4 mm	Generally poikilitically enclosed within plagioclase.
Websterite	Clinopyroxene	65-85%	0.4 to 3 mm	Anhedral; generally cloudy owing to exsolution blebs.
	Orthopyroxene	10-25%	0.1 to 3 mm	Anhedral with ragged edges except for subhedral to euhedral terminations within plagioclase.
	Plagioclase	<10%	<0.5 mm	Interstitial.
	Olivine	0-10%	<0.4 mm	Resorbed, subrounded grains poikilitically enclosed within both pyroxenes.
Melanorite	Orthopyroxene	60-80%	0.5 to 2 mm (rarely to 5 mm)	Subhedral, generally tabular.
	Plagioclase	10-30%	Up to 2 mm	Interstitial, subhedral grains; also as laths subophitic to optically enclosed within orthopyroxene.
	Clinopyroxene	<5%	<1 mm	Interstitial or intergrown with orthopyroxene.
	Olivine	0-10%	0.1 to 2 mm	Subrounded 0.1 to 0.2 mm grains are poikilitically enclosed within orthopyroxene and plagioclase.
Augite	Orthopyroxene	45-60%	1.5 x 0.4 mm (tabular)	Common ragged appearance; often intergrown with clinopyroxene.
Melanorite	Plagioclase	20-30%	0.5 mm (prismatic) <1.5 mm	Interstitial, anhedral grains; also as laths subophitically enclosed within orthopyroxene.
	Clinopyroxene	10-25%	Up to 1.5 mm	Ragged, anhedral grains intergrown with orthopyroxene.
	Olivine	0-5%	0.05 to 0.2 mm	Resorbed grains poikilitically enclosed within plagioclase and orthopyroxene.



Photo 11.5. Melatroctolite occurring as an inclusion. Rounded olivine grains enclosed within a larger crystal of plagioclase. Crossed nicols. 44X.

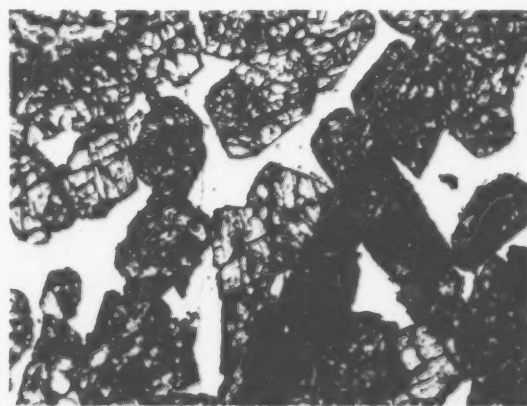


Photo 11.6. Mafic norite. Subhedral hypersthene enclosed poikilitically in plagioclase. Crossed nicols. 50X.

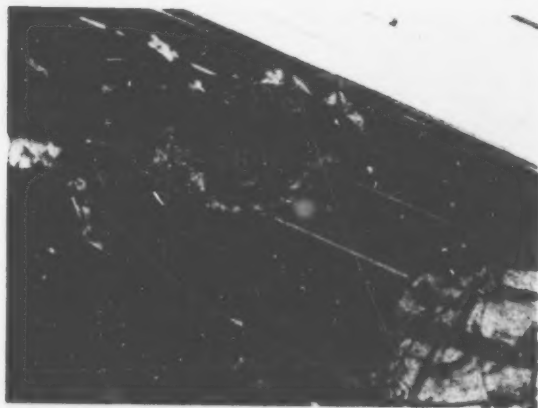


Photo 11.7. Olivine melanorite occurring as an inclusion. Coronas of orthopyroxene developed at the contact of olivine and enclosing plagioclase. Crossed nicols. 175X.

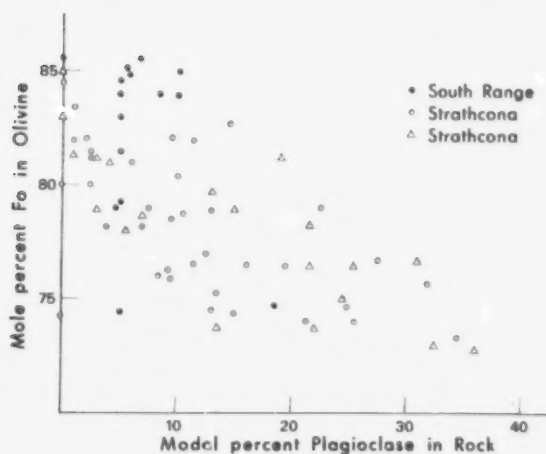


Figure 11.19. Plot of Fo content of olivine versus the modal content of plagioclase for samples of mafic and ultramafic inclusions in the sublayers (after Scribbs *et al.* 1984).

1. The inclusions occur in plutonic tholeiitic Sublayer rocks and range up to several m in diameter, whereas mantle nodules are found in alkali basalt or kimberlite hosts and rarely exceed 50 cm in diameter.
2. Harzburgite, wehrlite, pyroxenite, websterite, norite, and gabbro are the most common Contact Sublayer inclusion rock types, whereas mantle nodules are primarily spinel lherzolite, garnet lherzolite, and eclogite. The presence of plagioclase in many of the inclusions implies a depth of 25 to 30 km or less for final equilibration (Green and Hibberson 1970), thus indicating a crustal origin.
3. The inclusions have cumulus textures, common to layered complexes, whereas mantle nodules are often metamorphic tectonites with plastic flow and other solid-state deformation features.

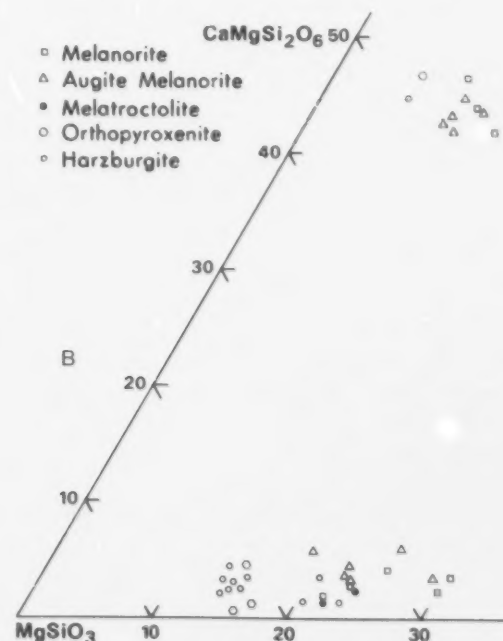
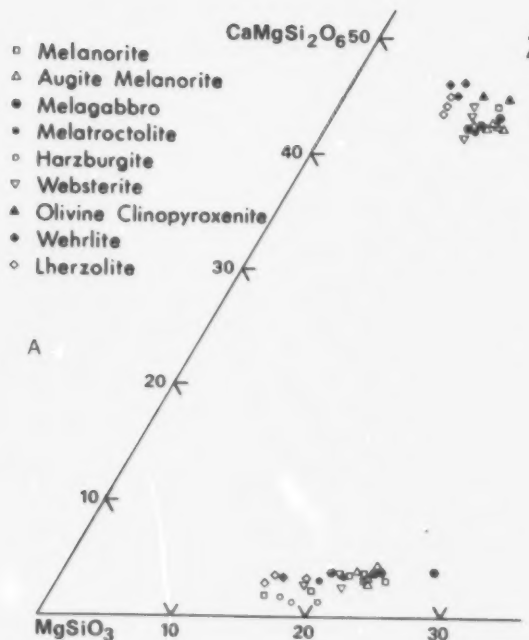


Figure 11.20a and 11.20b. Pyroxene compositions from mafic and ultramafic inclusions in the Contact Sublayer of the North and South Ranges plotted on the pyroxene quadrilateral (after Scribbs *et al.* 1984).

4. Textural evidence indicates that olivine in the inclusions has reacted with intercumulus liquid to form orthopyroxene, a process believed to occur only at low pressures (< 5 kb), especially if the parent magma was relatively dry (Kushiro 1969).
5. Olivine compositions in the inclusions are generally $Fo_{73.4}$ to $Fo_{85.6}$, a range common to many lay-

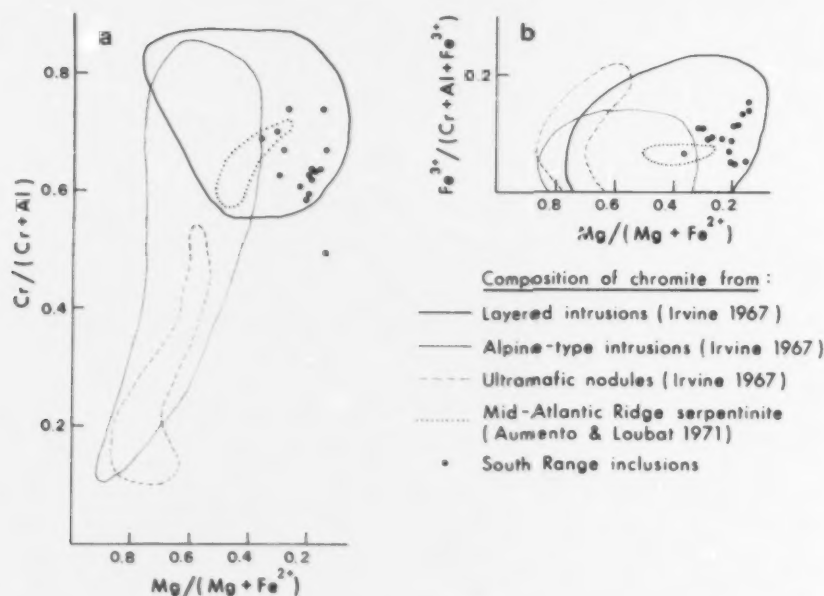


Figure 11.21. Compositions of chromites from mafic and ultramafic Contact Sublayer inclusions plotted on sections through the chromite prism of Irvine (1965) (after Scribbs *et al.* 1984).

ered intrusions (Fo_{80} to Fo_{90} in the Stillwater Complex, Jackson 1967; Fo_{70} to Fo_{85} in the Muskox Complex, Irvine and Smith 1967), whereas olivine from mantle nodules commonly is in the range Fo_{88} to Fo_{94} (Ringwood 1975).

6. The chromite in the inclusions is more like that in layered intrusions than in mantle-derived materials (Figure 11.21).

Pattison (1979) suggested that some of the inclusions may have been derived from pre-Sudbury Igneous Complex anorthosite-gabbro-pyroxenite bodies related to the Nipissing Diabase and also from mafic gneisses of the Levack Gneiss Complex. Olivine, in amounts up to 25 modal %, is, however, only present in intrusions of the Nipissing Diabase in the Cobalt area (Card and Pattison 1973). The layered gabbro-anorthosite complex described by James and Harris (1977) is similar to others in the vicinity of Sudbury, but does not contain olivine. Thus, bodies that may be correlated with reasonable confidence with the Nipissing Diabase are not an obvious source of the whole range of inclusions that have been observed.

However, Hewins (1971) indicated the intersection of a 150 m thick, peridotite-pyroxenite sill by 3 drillholes in the Archean gneiss forming the Footwall of the ore zone in the Fraser section, 2 km west of the Strathcona Mine on the North Range. He provided no details of this sill and none have appeared elsewhere in the literature (see Coats and Snajdr, Chapter 14, this volume), so that its significance as a source of the inclusions is uncertain. It would be unlikely that a re-

lated sill would be present at the very different stratigraphic level represented by the Huronian rocks constituting the Footwall along the South Range, so that while it may be the source of some inclusions along the North Range, it, or a relative, is unlikely to be the source of those along the South Range. It could, however, be the source of the clinopyroxene-bearing inclusions that have only been observed at the Strathcona Mine, and thus be the explanation for this anomaly.

Scribbs *et al.* (1984) concluded that the inclusions represent fragments of one or more hidden layered complexes. The magma(s) giving rise to the inclusions was (were) less fractionated than that (those) giving rise to the Sudbury Igneous Complex. Furthermore, Kuo (1976) has drawn attention to the similarity between the shape of the REE profiles of the Contact Sublayer inclusions and the Contact Sublayer magmas themselves, with the inclusions having lower REE contents. Both of these observations are consistent with the model that the magma responsible for the inclusions was co-genetic with that giving rise to the Sudbury Igneous Complex. However, Scribbs *et al.* (1984) emphasized that none of the available data provide conclusive proof of this model.

ASSOCIATION WITH MINERALIZATION

Naldrett and Kulierud (1967) found a close association between the sulphide assemblage characteristic of the ore deposits, pyrrhotite-pentlandite-chalcopyrite, and the Contact Sublayer (see Figure 11.22). The Sub-

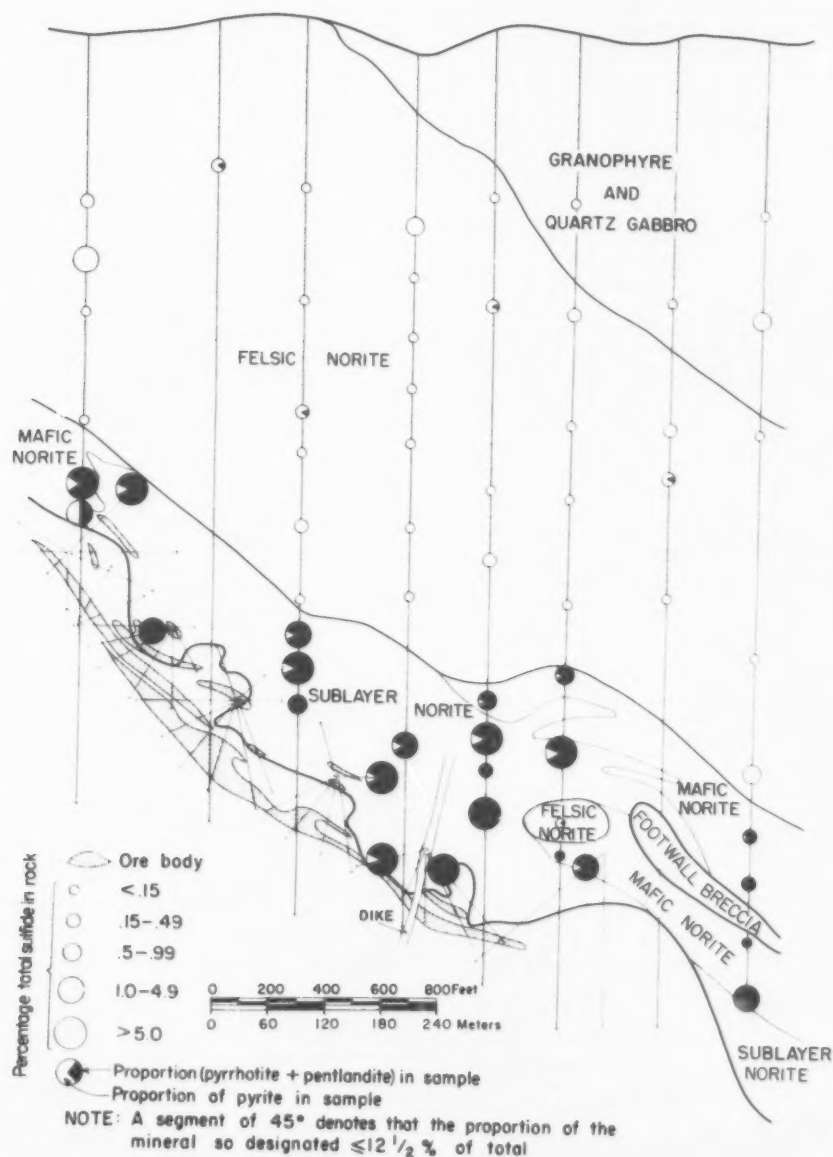


Figure 11.22. Vertical cross-section through the Strathcona Deposit illustrating the close association between the sulphide assemblage, pyrrhotite-pentlandite, and the Contact Sublayer (after Naldrett and Kullerud 1967).

layer at the Strathcona Mine contains 1 to 5 modal % sulphide, in marked contrast to the overlying felsic norite, which not only contains much less sulphide, but has the dominant sulphide as pyrite.

It should be noted, however, that the distinction between the Contact Sublayer and the mafic norite is not so clear cut. The latter contains just about as much of the same pyrrhotite-pentlandite-chalcopyrite assemblage as the former. Pattison (1979) commented that the basal units of the Main Mass of the Complex contain appreciable ore-type sulphide only when they

directly overlie Contact Sublayer, and concluded that the Main Mass has been contaminated by Contact Sublayer at these places. On the other hand, Duke and Naldrett (1977) have shown that the ratio of pyrite/(pyrrhotite + pentlandite + chalcopyrite) decreases with decreasing stratigraphic height in the Complex, and because the mafic norite is the least fractionated part of the Complex, it would be expected to have the highest proportion of pyrrhotite-rich sulphide. Whatever its origin, the Contact Sublayer is by far the most important rock unit of the Sudbury Igneous Complex so far as mineralization is concerned.

RELATIVE AGE OF THE SUBLAYER

Radiometric age dating indicates that the Contact Sublayer is similar in age to the Main Mass of the Complex, but an exact relative age relationship is essential to understanding how the sulphide ore formed. In this paper, we describe contact relationships between Contact Sublayer and Main Mass norite from the South Range that indicate that the Contact Sublayer is the younger, although this variant of the Contact Sublayer is not mineralized. Grant and Bite (Chapter 12, this volume) also reported xenoliths of Main Mass norite in the Contact Sublayer, from ore deposits on the South Range.

On the other hand, Pattison (1979), pointing to inclusions of massive ore in the Main Mass norite, the termination of internal structures in the Contact Sublayer by the Main Mass (for examples as seen at Whistle, Figure 11.3), and the occurrence of mineralized Main Mass norite only when it is underlain by mineralized Contact Sublayer, argued that the Contact Sublayer is older. He also argued that it is difficult to explain why the Main Mass had not filled the fractures occupied by the offsets if it were the older.

Observations bearing on the relative ages of the Contact Sublayer and Main Mass are contradictory, and it seems that both were emplaced at much the same time, with one slightly ahead of the other and *vice versa* in different localities. The Sr isotope initial ratios and REE patterns indicate a close similarity in magma type, a magma that is unusual in that it seems to have been modified by considerable interaction with crustal rocks. In the Summary chapter to this book, a model is proposed that presents the views of one of the authors of this section (A.J. Naldrett) and suggests a scenario as to how Main Mass, Contact Sublayer, and inclusions may be related.

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CHAPTER 12

Sudbury Quartz Diorite Offset Dikes

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ABSTRACT

Quartz diorite is the dominant Sublayer rock of the Sudbury Igneous Complex. It comprises the largest part of the offset dikes that extend radially from the Complex or lie concentrically about it in the Footwall. The offset dikes are host to many of the large Ni-Cu sulphide deposits at Sudbury.

The morphology of the offset dikes and their contact relationships suggest that quartz diorite magma was injected into breccia-filled fracture zones at a time when the temperature of the Footwall rocks was elevated. Several petrographic variants of quartz diorite, resulting from assimilation, quick cooling, and alteration are recognized. Country rock and exotic (gabbroic to ultramafic) xenoliths are abundant. Locally abundant xenoliths of basal Sudbury Igneous Complex rocks, suggest that quartz diorite magma intruded after solidification of the Lower Zone.

Assimilation of country rock material is demonstrated by compositional variation near offset dike margins which is sympathetic with adjacent country rock composition. Consideration of least-altered, least-contaminated samples indicates compositional homogeneity among South Range offset dikes and among North Range offset dikes, but marked compositional differences between South Range and North Range offset dikes. These differences are paralleled by differences between South Range quartz gabbro of the Middle Zone, and North Range quartz gabbro. On most oxide variation diagrams, quartz diorite occu-

pies a position intermediate between Main Mass norite and quartz gabbro. The geochemical evidence suggests that quartz diorite is related to the upper noritic units of the Lower Zone.

The intermediate composition of quartz diorite rules out *in situ* precipitation of the volumes of sulphide present. This, along with the correlation of sulphides with high xenolith populations suggests that quartz diorite was not the source for the sulphides, but merely the transport medium.

INTRODUCTION

In the Sudbury Igneous Complex, the major ore deposits at the Frood, Stobie, Clarabelle, Copper Cliff North, and Copper Cliff South Mines are all associated with quartz diorite, a member of the Sublayer group of rocks (Souch, Podolsky *et al.* 1969). Quartz diorite is the dominant Sublayer rock type within the dike-like offsets, which extend either radially away from the Sudbury Igneous Complex or strike parallel to it within the surrounding Footwall rocks (Figure 12.1). In the past, the terms "quartz diorite" and "quartz diorite breccia" have been widely, and sometimes incorrectly, applied to various Sudbury rock types, resulting in considerable confusion. In this study, the several varieties of Sudbury quartz diorite are compared and their relationships to other rocks of the Sudbury Igneous Complex are discussed. An interpretation of the formation of the offset dikes and

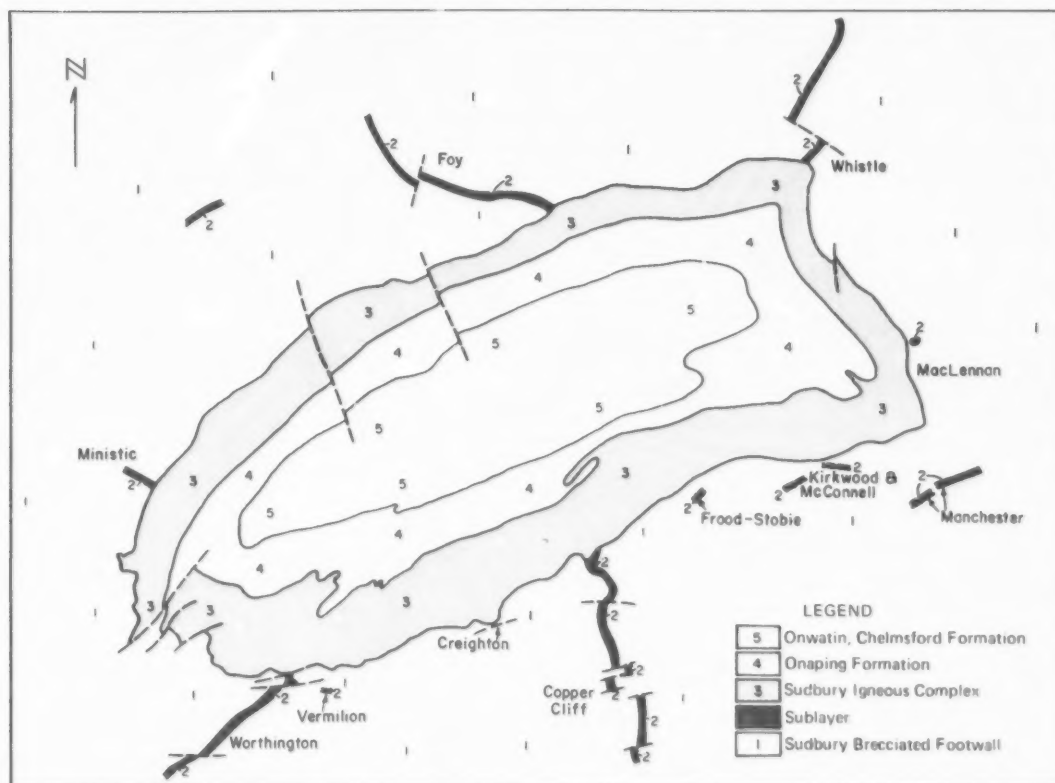


Figure 12.1. Offset dikes of the Sudbury Igneous Complex.

their genetic relationship to the Main Mass of the Sudbury Igneous Complex is presented in the final section. The petrographic and morphological descriptions are summaries of data accumulated over the past several years; the geochemistry section is based on recently acquired data.

Previous Work

Coleman (1905) first applied the term "offsets" to the quartz diorite dikes which radiate outward from the Main Mass of the Sudbury Igneous Complex. He noted the remarkable homogeneity of the rock within the major offset dikes but, although he believed that they were genetically related to the Complex, he did not resolve their age relationships. Collins (1934) agreed with Coleman on the genetic relationship and, in addition, postulated that the offset dikes were formed by magma that had escaped into the Footwall during the final phases of norite differentiation. Burrows and Rickaby (1935) suggested that the quartz diorite offset dikes were younger than the Main Mass. Yates (1938) agreed with Burrows and Rickaby and cited numerous field observations as supporting evidence. Thomson (1935) demonstrated that the average chemical composition of quartz diorite is intermediate between that of norite and micropegmatite, and he suggested that

this composition represented the parental magma composition prior to differentiation. Slaughter (1951) studied the proximal part of the Copper Cliff Offset Dike and concluded that the norite-gabbro (for example, the basal Main Mass norite) is gradational into quartz diorite, thereby confirming the genetic relations between the two. Pattison (1979) noted that the difference between the marginal gabbro-norites in the Main Mass and the offset dike quartz diorite is possibly a result of deuterite alteration. Morris and Pay (1981) suggested, on the basis of paleomagnetic evidence, that the offset dikes were formed by a series of separate magmatic pulses intruded in the same sequence as the Main Mass of the Sudbury Igneous Complex, and further suggested that the tectonic evolution of the Main Mass is paralleled by that of the offset dikes in the adjacent Footwall. Various other authors have also discussed the offset dikes in conjunction with their studies of the Sublayer (Naldrett, Greenman, and Hewins 1972; Souch, Podolsky *et al.* 1969, and so on).

GENERAL DESCRIPTION OF THE OFFSET DIKES

Quartz diorite occurrences may be divided into the following 3 types, according to their location and attitude

with respect to the Main Mass of the Sudbury Igneous Complex.

1. *Radial offset dikes*

These begin at embayments of the Footwall contact of the Main Mass and extend into the surrounding country rocks for several km like the spokes of a wheel (for example, the Foy, Copper Cliff, and Worthington Offset Dikes).

2. *Parallel or concentric offset dikes*

These are continuous to semi-continuous dikes of quartz diorite which strike parallel to the lower contact of the Main Mass in zones of massive Sudbury Breccia (for example, Frood-Stobie and Manchester Offset Dikes).

3. *Discontinuous quartz diorite occurrences*

These are small bodies of quartz diorite within embayment structures that are mostly filled with other Sublayer rocks (for example, Creighton and MacLennan).

The morphology of the pre-existing Footwall, specifically the presence of major radial structures and Sudbury Breccia zones, are interpreted as having been the dominant factors in determining the shape and attitudes of the dikes. In the following descriptions, emphasis is placed on shapes and attitudes of the offset dikes, and on their contact relationships with the country rocks, and with Sudbury Breccia.

Radial Offset Dikes

FOY OFFSET DIKE

The Foy Offset DiKE has been traced for 28 km from the North Range of the Sudbury Igneous Complex into the Archean granitic country rocks (Figure 12.2). It narrows from approximately 400 m wide at the Main Mass contact in Bowell Township to 15 to 30 m in its most distal part in Hess Township. Near the contact with the Main Mass, the Foy Offset DiKE contains a variety of Sublayer rocks (Pattison 1979). A quartz-poor variety of xenolithic norite occupies the core of the embayment and is mantled by quartz-rich xenolithic norite, in which the interstitial quartz, granophyric intergrowths of quartz and orthoclase, and microcline increase in abundance toward the Footwall contact. The closest occurrence of quartz diorite to the Main Mass is approximately 3 km outward along the dike. Contacts between quartz diorite and xenolithic norite have not yet been delineated, but occur between the Nickel Offset Mine and Foster Lake (Figure 12.2); contacts between xenolithic norite and the Main Mass of the Sudbury Igneous Complex are not exposed.

Where the offset dike is proximal to the Main Mass (Figure 12.2), it has sharp contacts with its country rocks, and there is little alteration developed in the immediately adjacent host rocks. The contacts of the dike are not always parallel in this part as there are

many small embayments and apophyses of offset dike rock protruding into adjacent country rock. Farther to the northwest, the offset is more dike-like and maintains a consistent thickness. There is little Sudbury Breccia next to the offset dike, but there is an abundance of Footwall Breccia within it occurring as bodies which alternate with bodies of quartz diorite within the offset, suggesting their simultaneous emplacement (Pattison 1979). Sulphides occur as pods and disseminations within both the Footwall Breccia and the Sublayer rocks.

At the Nickel Offset Mine, the offset dike is up to 120 m wide. Quartz diorite is the only Sublayer rock present. Xenoliths up to 15 m in diameter are primarily composed of locally derived granitic, migmatitic, gabbroic, and metavolcanic rocks. Relatively sulphide-deficient and xenolith-poor marginal zones enclose a core of sulphide-rich and xenolith-rich quartz diorite. The concentration of sulphides and xenoliths in the dike core may be caused by the velocity gradient across the dike during its emplacement (Komar 1972). If so, this implies that the sulphides were discrete solid, or semi-solid xenoliths or liquid blebs when the quartz diorite was intruded. In places, pods of massive sulphide up to 60 m long occur within the quartz diorite (Card and Meyn 1969).

The most distal part of the offset dike, in Hess Township, consists of a narrow, mineralized vertically dipping dike of quartz diorite within Sudbury Breccia (Card and Innes 1981). This part of the dike strikes parallel to the Sudbury Igneous Complex Footwall contact to the south. The abrupt change in strike of approximately 90° is assumed to have occurred in that part of the offset dike that is now missing. Similar changes in strike occur in the Copper Cliff and Whistle Offset Dikes. These abrupt changes in strike are significant because they suggest that there is a direct relationship between radial and parallel offset dikes, and that the emplacement of both types was controlled by pre-existing structural weaknesses in the Footwall rocks.

WHISTLE OFFSET DIKE

The Whistle Offset DiKE strikes northeast from the northeastern corner of the Main Mass of the Sudbury Igneous Complex (Figure 12.3). It extends for 1.5 km from the contact, at which point it is displaced 2 km to the northwest by a fault, and then continues for an additional 3.5 km to the northeast.

The Whistle Offset DiKE begins as a 350 m wide embayment in the Footwall of the Sudbury Igneous Complex. It narrows and contains an increasingly quartz-rich suite of Sublayer rocks to the northeast and at depth. Beyond a point approximately 450 m from the Main Mass contact, the poorly exposed offset dike is only 10 to 30 m wide, and contains large pods of hy-

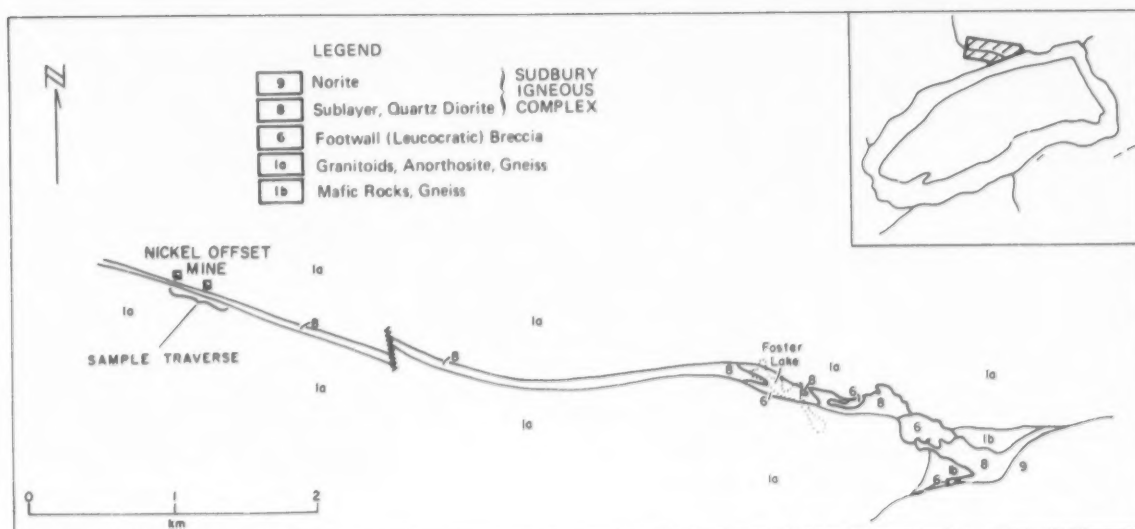


Figure 12.2. Foy Offset Dike (Proximal Portion).

persthene quartz diorite within a colinear envelope of siliceous, recrystallized Footwall Breccia. Sulphide mineralization is present both within the Sublayer rocks of the embayment and in the quartz diorite and Footwall Breccia of the offset dike itself. The country rocks adjacent to the offset dike include granodiorite, diorite, gabbro, and gneiss, all of Archean age.

Northeast of the fault (Figure 12.3), the offset dike intrudes Huronian metavolcanic and metasedimentary rocks which are poorly exposed. Diamond drilling indicates that the dike extends for more than 3 km with the same northeast strike. In the vicinity of the Milnet Mine (Figure 12.3), the offset abruptly turns to the northwest and continues for an additional 500 m. This distal segment is reported to consist of amphibole-biotite quartz diorite with xenoliths of country rock up to 2 m in diameter (Meyn 1970). Xenoliths comprise from 10 to 90% of the dike rock. The sulphide mineralization at the Milnet Mine occurs as massive pods in quartz diorite and in associated Sudbury Breccia.

COPPER CLIFF OFFSET DIKE

The Copper Cliff Offset Dike begins as a 1500 m wide, funnel-shaped embayment of the Sudbury Igneous Complex in Snider Township (Figure 12.4). It narrows quickly to a width of 20 to 75 m and extends due south for approximately 19 km, segmented in several places by west-trending faults. Segments south of Kelley Lake (the distal part) are mineralogically and chemically distinct from the remainder of the offset to the north (the proximal part), although they do have similar strikes, xenoliths, and minor but ubiquitous sulphides. The most distal segment is < 10 m wide.

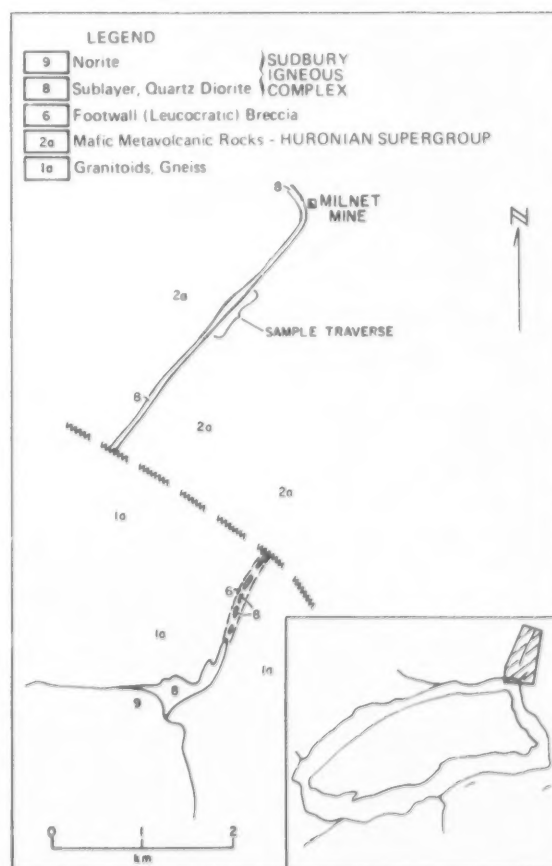


Figure 12.3. Whistle Offset Dike.

Within the embayment proper, in the vicinity of the Copper Cliff North Mine, basal quartz-rich norite (Table 12.1) grades over several m into amphibole-biotite quartz diorite. Marginal Sublayer rocks, chiefly biotite quartz diorite, become more abundant to the south. Sudbury Breccia is common in the country rocks around the offset dike, but in most places, the dike rocks are in direct contact with unbrecciated country rock. In the distal part of the offset, Sudbury Breccia becomes less common and contacts of the dike with its country rocks, principally Huronian metavolcanic and metasedimentary rocks, are generally sharp. Chilling of the margins of the offset dike rocks near the embayment is minor, but is more pronounced in the distal parts of the dike. Spherulitic textures, presumably indicative of rapid cooling, are common at the dike margins, especially in the distal parts. Considerable modal and textural variation exists in the quartz diorite. Comparative mineralogy suggests that the local quartz and granophyre contents are directly related to the quartz content of adjacent country rock. The same relationship has been noted in the Worthington and Manchester Offset Dikes, and is also indicated by variations in chemical composition. Apparently, assimilation of country rock has significantly affected the composition of the quartz diorite.

Cryptic banding, defined by alternating 1 to 2 m wide bands of granophyric and non-granophyric amphibole quartz diorite, has been observed at the Copper Cliff South Mine (W.V. Peredery, Staff Geologist, Inco Limited, personal communication, 1983). The cause of the banding is not yet understood, but it may represent primary magmatic layering.

Much of the segmentation of the offset dike has been caused by faulting, but there appear to be several instances where the segmentation represents primary *en echelon* emplacement (Cochrane, Chapter 15, this volume). In these cases, the segments have smooth, lobate ends, and no faulting is evident. Similar examples have been noted in the Foy Offset Dike in Leinster Township north of the Sudbury Igneous Complex.

In one of the most distal segments south of the Makada Fault (Figure 12.4), the dike is < 10 m wide and slightly chilled against Mississagi quartzite along both sides. Two phases of quartz diorite are apparent here; one is a fine-grained, biotite-rich variety which occurs as irregular, lobate inclusions up to 1 m in diameter within the other variety, which is medium grained. This matrix is highly charged with fragments of fine-grained gabbro, that were probably transported from one of the Sudbury gabbro sills situated several hundred m to the north.

A detailed description of the Copper Cliff Offset Dike and its orebodies is given by Cochrane (Chapter 15, this volume).

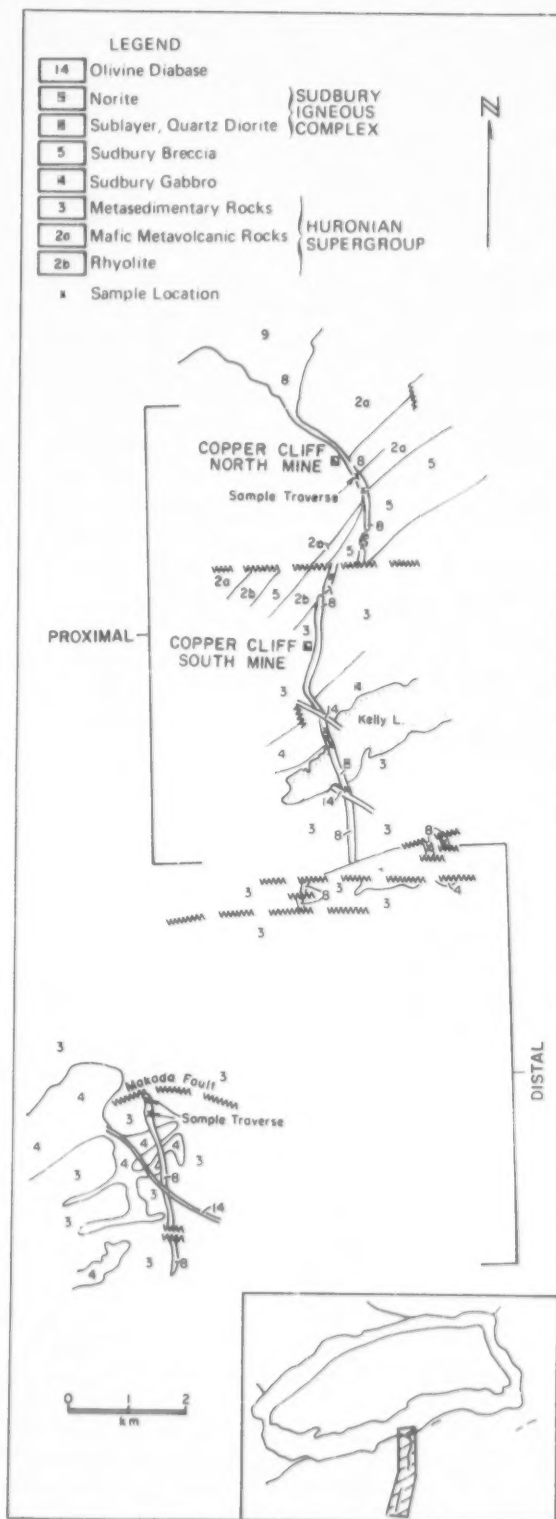


Figure 12.4. Copper Cliff Offset Dike.

WORTHINGTON OFFSET DIKE

The Worthington Offset DiKE is a branching offset, that extends to the southwest from Denison Township to Lorne Township, a distance of approximately 15 km (Figure 12.5). The proximal part, perhaps originally occupying an embayment in the footwall similar to those at the Copper Cliff and Foy Offset Dikes, presently occurs as large faulted segments in fault contact with the Main Mass of the Sudbury Igneous Complex. Reconstruction of the segments indicates that the offset extended south from the Complex, narrowed slightly, and then broadened before bifurcating. The eastern limb tapers gradually for a distance of 1500 m at the surface and plunges to the southeast, broadening with depth. The western limb extends to the southwest for at least 15 km, with a relatively uniform thickness of 70 m.

Generally, the dike contacts presently dip 60° to 70° SE in the proximal part, are near vertical in the eastern limb, and dip approximately 80° SE in the western limb. Contacts between quartz diorite and country rocks are knife-sharp; the grain size of the quartz diorite is only slightly reduced near contacts. Sudbury Breccia is not abundant in the Huronian me-

ta volcanic and metasedimentary rocks into which the offset is intruded.

Sulphides in the offset dike occur as pipe-shaped, subvertical ore deposits (Victoria, Kidd Copper, and Totten Mines), as gossanous zones particularly along the dike margins, and as widely disseminated, elongate sulphide blebs, up to 1 to 2 cm in length. In places, up to 75% of the dike (by area) consists of xenoliths of almost entirely local derivation (Card 1968). Less common, but of genetic and volumetric significance in mineralized areas, are exotic xenoliths of altered pyroxenite and gabbro of unknown derivation. Similar exotic xenoliths occur in much of the Sublayer of the Sudbury Igneous Complex. Both the country rock and the exotic xenoliths vary in diameter from < 1 cm to several m.

The Worthington Offset DiKE consists of medium-grained, compositionally variable amphibole-biotite quartz diorite. Other Sublayer rock types are absent, even adjacent to the Main Mass of the Sudbury Igneous Complex, except for coarse-grained xenoliths. The latter occur within quartz diorite both as distinct rounded xenoliths up to 2 m across and as small, poorly defined patches and individual plagioclase xenocrysts. These xenoliths, which are mineralogi-

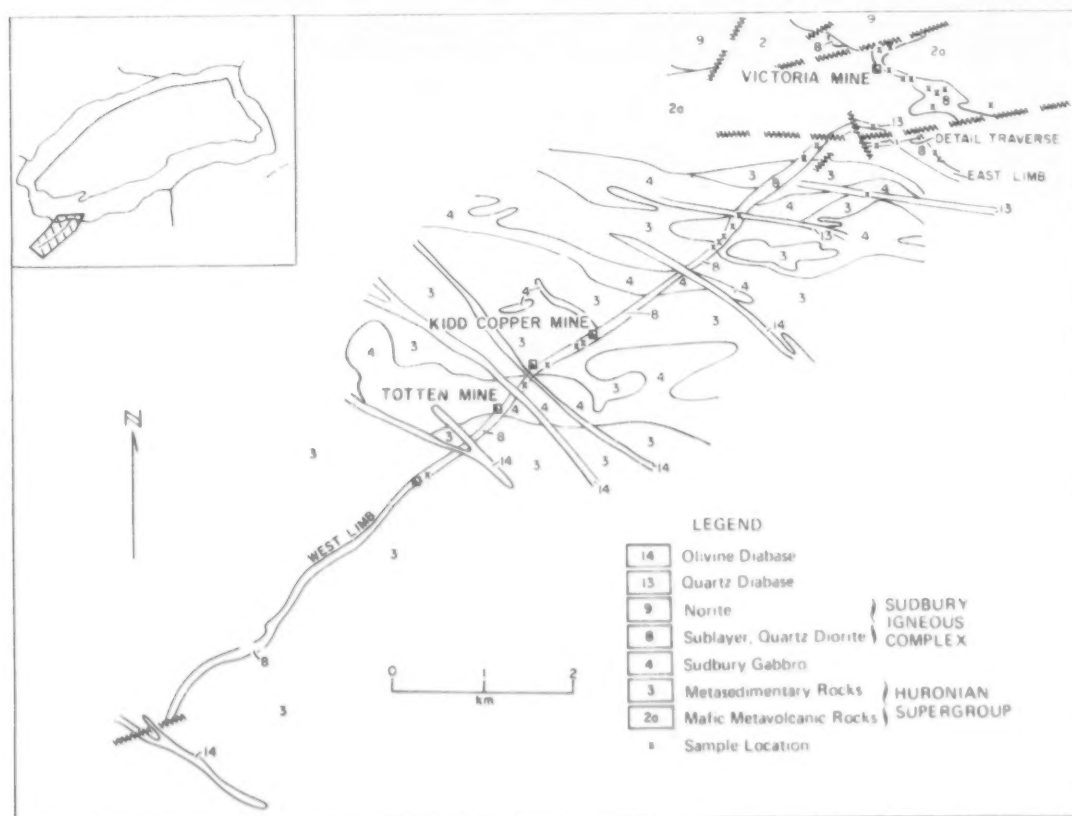


Figure 12.5. Worthington Offset DiKE.

CHAPTER 12

TABLE 12.1: OFFSET DIKE ROCKS.

		RADIATING OFFSET DIKES					PARALLEL OFFSET DIKES				DISCONTINUOUS OCCURRENCES			
		Copper Cliff	Worthington	Whistle	Foy	Ministic	Flood- Stobie	Kirkwood	McConnell	Manchester	Vermilion	Creighton	MacIsaac	
MAIN DIKE	SUBLAYER ROCKS													
		Xenolithic norite			1,2 3,4 A	1,2 3,4 A	1,2 3,4 A							
	Pyroxene sublayer			2,4 B			2,4 C					1,2 3,4 B		
	MAIN MASS	Basal norite	1,2 3,4 A	1,2 3,4 A								1,2 3,4 A		
		QUARTZ DIORITE (QD)												
	Hypersthene QD	1,3 B		2,4 A	1,2 3,4 A	1,2 3 A								
	Pyroxene QD	1,2 3,4 B	1,2 3,4 B											
	Amphibole-biotite QD	1,2 3,4 A	1,2 3,4 A	1,2 3,4 A		1,2 3 A	1,2 3,4 B	1,2 3,4 A	1,2 3,4 A		1,2 3,4 A	1,2 3,4 A	1,2 3,4 B	
	CONTAMI- NATED	Granophyric QD									1,2 3,4 A			1,2 3,4 B
		Quartz-rich QD									2,4 A			1,2 3,4 A
CONTACT	Biotite QD	1,2 3,4 B						1,2 3,4 C	1,2 3,4 C					
	Spherulitic QD	2,4 C	2,4 C	2,4 C	2,4 C		2,4 B	2,4 B	2,4 C					

Key:

- 1-mineralized
- 2-unmineralized
- 3-inclusion-bearing
- 4-inclusion-free
- A-major unit
- B-minor unit
- C-rare unit

cally and texturally similar to basal quartz-rich norite, have been observed on both the eastern limb and at least as far south as Totten Mine on the western limb; larger xenoliths of this type occur in the proximal part of the offset.

The presence of basal quartz-rich norite xenoliths in the quartz diorite of offset dikes suggests that quartz diorite dike emplacement occurred after solidification of at least the lower part of the Main Mass of the Complex.

MINISTIC OFFSET DIKE

The Ministic Offset Dike in Cascaden Township has not been examined in detail, but limited petrographic

work indicates that it is probably a smaller scale equivalent of the Foy Offset Dike. Sublayer rocks and Footwall Breccia fill a small embayment structure in the proximal part of the offset dike, but quartz diorite is the dominant facies in the distal part.

SUMMARY

From the above descriptions, the radial offset dikes appear to have a number of features in common:

1. The radial offset dikes all extend outward from the Main Mass of the Sudbury Igneous Complex for 10s of km into the Footwall rocks. The offset dikes generally have a near vertical dip.

2. The radial offset dikes are connected to the Main Mass by trough-shaped, sublayer-filled, Footwall embayments up to several hundred m wide. Within a few km distance from the Main Mass, the radial offset dikes narrow in width to a few 10s of m or less.
3. Emplacement of the offsets beyond the embayments seems to have been controlled by pre-existing Footwall structures, specifically radial fracture zones and concentric breccia zones, as illustrated by the abrupt changes in strike and bifurcations.
4. There is a gradational change between the other Sublayer rocks (*see* section on "Petrography") in the offset dikes near the Main Mass, and quartz diorite in the offsets 1 to 2 km from the Main Mass.
5. Contacts with country rocks are knife-sharp; the slight decrease in grain size at the margins of the dikes indicates little or no chilling. Adjacent country rocks show little obvious thermal metamorphism near offsets; perhaps because the entire Footwall was relatively hot at the time of quartz diorite intrusion.
6. There are generally only small amounts of massive Sudbury Breccia adjacent to the offsets; significant amounts of Footwall Breccia are included within some offsets (Pattison 1979).
7. Most offset dikes have more xenoliths and sulphides in their central parts, probably the result of flow differentiation during emplacement. Country rock xenoliths locally make up to 90% of some offset dikes. Exotic xenoliths are common in heavily mineralized zones which suggests a genetic relationship between them and sulphides. Xenoliths of basal quartz-rich norite in quartz diorite constitute evidence that the offset dikes postdate the basal parts of the Main Mass of the Sudbury Igneous Complex.
8. Sulphides are ubiquitous as disseminated blebs, and locally as near-vertical, pipe-shaped massive bodies composed of chalcopyrite, pyrrhotite, and pentlandite.
9. Offset dikes may have more than one textural variety of quartz diorite.

Parallel or Concentric Offset Dikes

MANCHESTER OFFSET DIKE

The Manchester Offset Dike, located 5 km south of the Main Mass (Figure 12.6) in Falconbridge Township, is 12 to 30 m wide, and is approximately 5 km long. It strikes northeast, parallel to the lower contact of the Main Mass to which it has no apparent physical connection. It consists of discontinuous segments of highly variable, siliceous quartz diorite, enclosed within a colinear zone of massive Sudbury Breccia. Over part of its length, the dike is composed of quartz diorite pods up to 3 m in length aligned within Sudbury Breccia.

The enclosing Sudbury Breccia consists of locally derived quartzite and gabbro fragments in a fine-grained pulverized matrix. The fragments range from a few mm to 10s of m in diameter. Most of the contacts between quartz diorite and breccia are sharp, although minor shearing has imposed a foliation that locally obscures contact relationships. Textures range from medium grained within the offset dike to fine grained at its margins.

The offset dike contains both granophyre-rich and quartz-rich quartz diorite. The granophyre-rich type is partly mineralized and occupies the central part of the dike; the quartz-rich type is generally barren and occupies the dike margins.

McCONNELL AND KIRKWOOD OFFSET DIKES

Two morphologically similar offset dikes (McConnell and Kirkwood) occur in Garson Township (Figure 12.7). The McConnell Offset Dike extends from the

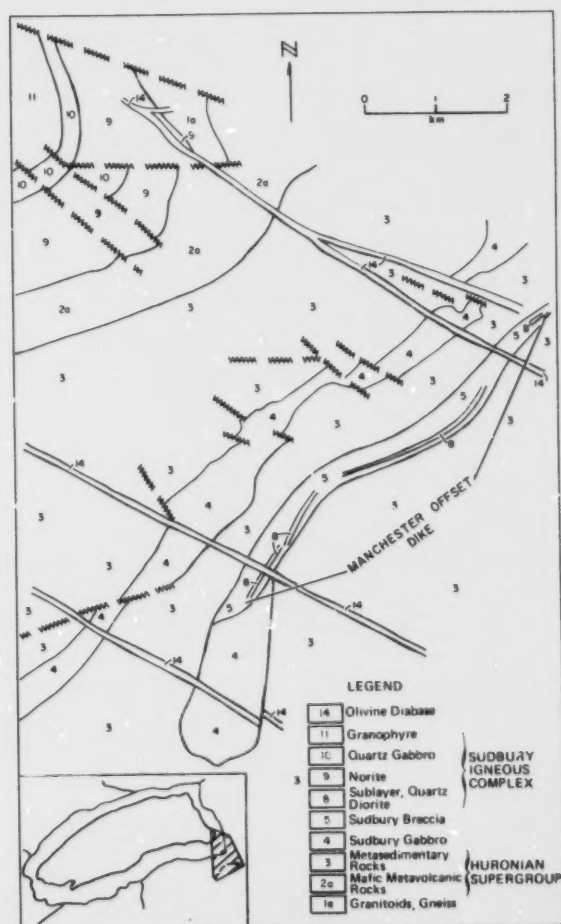


Figure 12.6. Manchester Offset Dike.

Main Mass contact at Kirkwood Mine southeast for over 1200 m. The Kirkwood Offset Dike, which is approximately 1500 m long, lies about 600 m south of the Main Mass and strikes east-west, parallel to the Main Mass contact. Both offset dikes are up to 60 m wide and consist of colinear, elliptical, amphibole-biotite quartz diorite pods contained in variably recrystallized and foliated Sudbury Breccia. Quartz diorite is the only Sublayer rock type present in these offsets.

The Sudbury Breccia host rock consists of locally derived Huronian metavolcanic and metasedimentary fragments with rare fragments of exotic gabbro and pyroxenite set in a fine-grained, recrystallized matrix composed of quartz, biotite, and feldspar, with minor amounts of chlorite and oxides. The matrix appears to be a recrystallized mechanical mixture of pulverized local country rocks. All fragments are subangular to rounded; they are commonly intruded by small stringers of Sudbury Breccia matrix. In some cases, 2 or more fragments can be obviously reassembled to form a larger fragment. The rims of many of the fragments weather easily, presumably the result of reaction with the enclosing breccia matrix.

Quartz diorite pods, although superficially similar to some of the fragments in the breccia, are in detail

quite different. The pods always occur as ellipsoids in contrast to subangular fragments. The pods do not have reaction rims, nor do they appear to have been intruded by breccia stringers. Also, the pods exhibit a slight variation in grain size from medium grained at the centres to fine grained at their edges, whereas the breccia fragments do not. One particular significant occurrence is a locally derived gabbro fragment, 25 cm in diameter, that was found straddling the contact between quartz diorite and Sudbury Breccia. In another case, a large fragment of amphibolite was found partly encased by a discontinuous 5 to 20 cm thick skin of very fine grained, slightly foliated biotite quartz diorite. The outer margin of the quartz diorite skin is in sharp contact with Sudbury Breccia. These relationships suggest that quartz diorite, despite its discontinuous nature, was emplaced as a liquid into pre-existing unconsolidated Sudbury Breccia; it was not present during the brecciation process. The quartz diorite pods contain xenoliths similar to fragments within Sudbury Breccia. In addition, the pods contain small (1 to 2 cm diameter), irregularly shaped feldspar-rich xenoliths which have been observed in varying numbers in other quartz diorite bodies. Sulphides occur within quartz diorite as 1 to 2 cm diameter blebs, and as disseminations in the breccia adjacent to quartz diorite pods. In

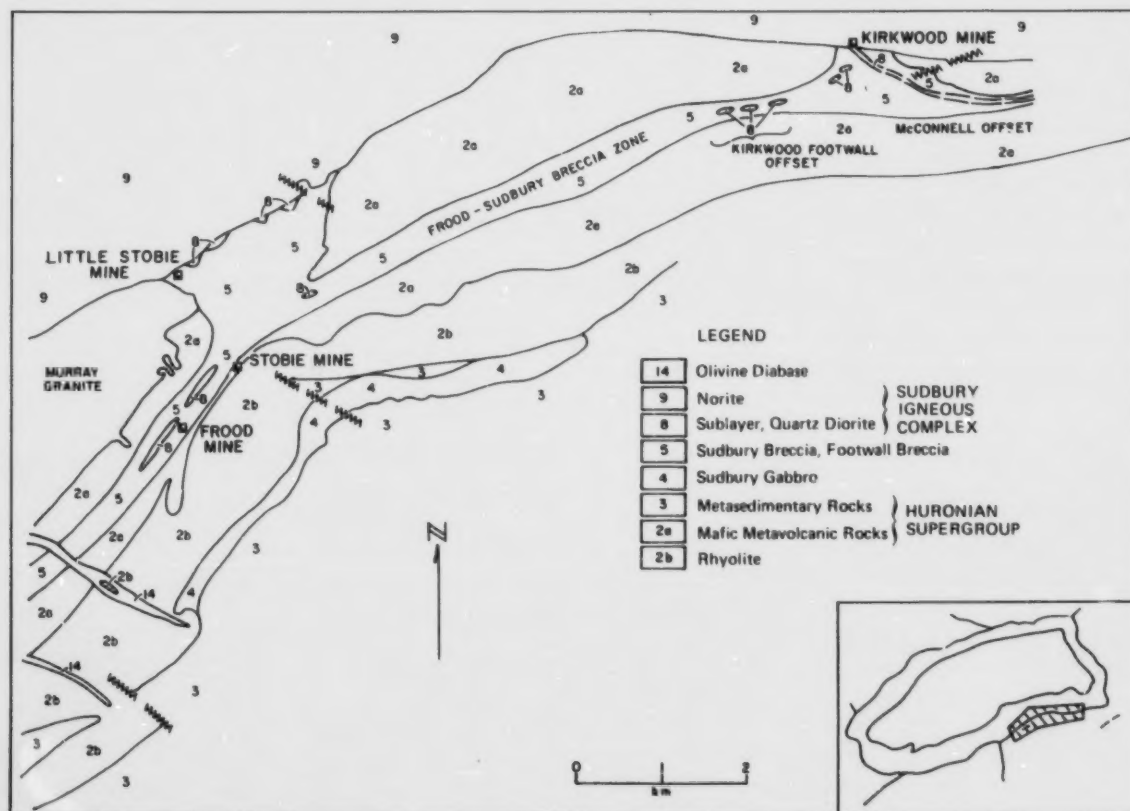


Figure 12.7. Frood-Stobie, Kirkwood, and McConnell Offset Dikes.

the McConnell Offset Dike near the Kirkwood Mine, massive sulphides occur mainly in breccia surrounding quartz diorite pods.

FROOD-STOBIE OFFSET DIKE

The Frood-Stobie Offset Dike lies parallel to and approximately 2 km from the lower Main Mass contact (Figure 12.7). It hosts the Frood and Stobie orebodies. The offset extends over a strike length of approximately 3 km and consists of pods of quartz diorite in a zone of mineralized and variably recrystallized Sudbury Breccia.

Souch, Podolsky *et al.* (1969, p.259) have described the Frood orebody as follows: "The deposit is huge, measuring 4300 feet long, 3500 feet deep, and 900 feet across at its widest part. It consists of a sulphide-spotted, wedge-shaped body of inclusion-bearing quartz diorite partly sheathed by inclusion-bearing sulfide." Igneous phases, chiefly amphibole-biotite quartz diorite, constitute about 10% of the silicate host rocks at Frood Mine; the remainder is recrystallized breccia.

The Stobie orebody lies approximately 1.6 km east of Frood along the offset. Relationships between quartz diorite, Sudbury Breccia, and sulphides are very similar to those at Frood. The relationship between the Frood and Stobie orebodies is shown in longitudinal section by Zurbrigg *et al.* (1957, p.346).

The Frood-Stobie Offset Dike lies west of a wide breccia zone that is in contact with the Main Mass. Coleman (1913, p.77) described the rocks in this zone: "The rocks in the neighbourhood of Stobie show the greatest variety found in the Sudbury District, including both eruptives and sedimentaries. To the north beside the greenstone and hornblende porphyries...there are rugged hills made up of "older norite" (pyroxene hornfels), orbicular diorites, pillow lavas...hornblende schist...". Where this breccia zone is in contact with the Sudbury Igneous Complex, it contains the Little Stobie orebodies (Davis, Chapter 16, this volume), but for the most part, the zone is barren of sulphide mineralization.

VERMILION OFFSET DIKE

The Vermilion Offset Dike in Denison Township is a northwest-striking zone, 200 m long, consisting of amphibole-biotite quartz diorite pods in a zone of massive Sudbury Breccia (Figure 12.8). It is apparently separated from the basal contact of the Main Mass of the Sudbury Igneous Complex, which is approximately 2 km to the north. The Vermilion Offset Dike is similar in many respects to the Kirkwood Offset Dike. The quartz diorite pods are ellipsoidal and display fine-grained textures at their edges. Well preserved spherulitic textures are present near the edges of some pods.

The pods contain local country rock xenoliths, exotic grey gabbro and pyroxenite xenoliths, and feldspar-rich xenoliths. The latter are described later in the section entitled "Petrography". As at Kirkwood, individual country rock fragments straddle contacts between the quartz diorite and its host Sudbury Breccia (Figure 12.8). In one locality, amphibolite inclusions occur along the contact; in another, rhyolite inclusions are strung like beads on a string along the quartz diorite-Sudbury Breccia contact, examples of the sharing of fragments between Sudbury Breccia and quartz diorite. In addition, a large grey gabbro fragment, about 6 by 9 m in size, is in sharp contact with quartz diorite on one side and Sudbury Breccia on the other. Sulphides occur within quartz diorite only as disseminated blebs; where present, massive sulphides occur as lenses within breccia that is closely associated with quartz diorite pods and exotic xenoliths.

Two pods reveal complex interfingering of coarse- and fine-grained textural varieties of amphibole-biotite quartz diorite. The coarse-grained variety appears to be present as inclusions within the fine-grained variety. This relationship has also been observed in the Copper Cliff Offset Dike and elsewhere. It suggests a complex cooling history for quartz diorite.

The quartz diorite pods and Sudbury Breccia are cut by east-trending dikes of quartz diabase (trap). Most of these diabase dikes are up to several m wide and have chilled borders. One 6 m wide dike which has been studied in detail is medium grained at its core, but grades into a fine-grained to aphanitic chilled zone, 10 to 20 cm wide at each margin. The chilling implies steep temperature gradients between the diabase magma and its country rocks. The margins of comparable quartz diorite offset dikes are much coarser grained, indicating that the country rocks were much hotter during the emplacement of the quartz diorite magma.

SUMMARY

The parallel or concentric offset dikes have the following common features:

1. The offset dikes strike parallel to the lower contact of the Main Mass of the Sudbury Igneous Complex, but lie 1 to 12 km away from it in the Footwall. They have no apparent physical connection to the Main Mass.
2. The offset dikes consist of discontinuous dike segments, or ellipsoidal pods of amphibole-biotite quartz diorite, within zones of massive, variably recrystallized Sudbury Breccia.
3. Quartz diorite is the dominant silicate Sublayer phase in these offsets.

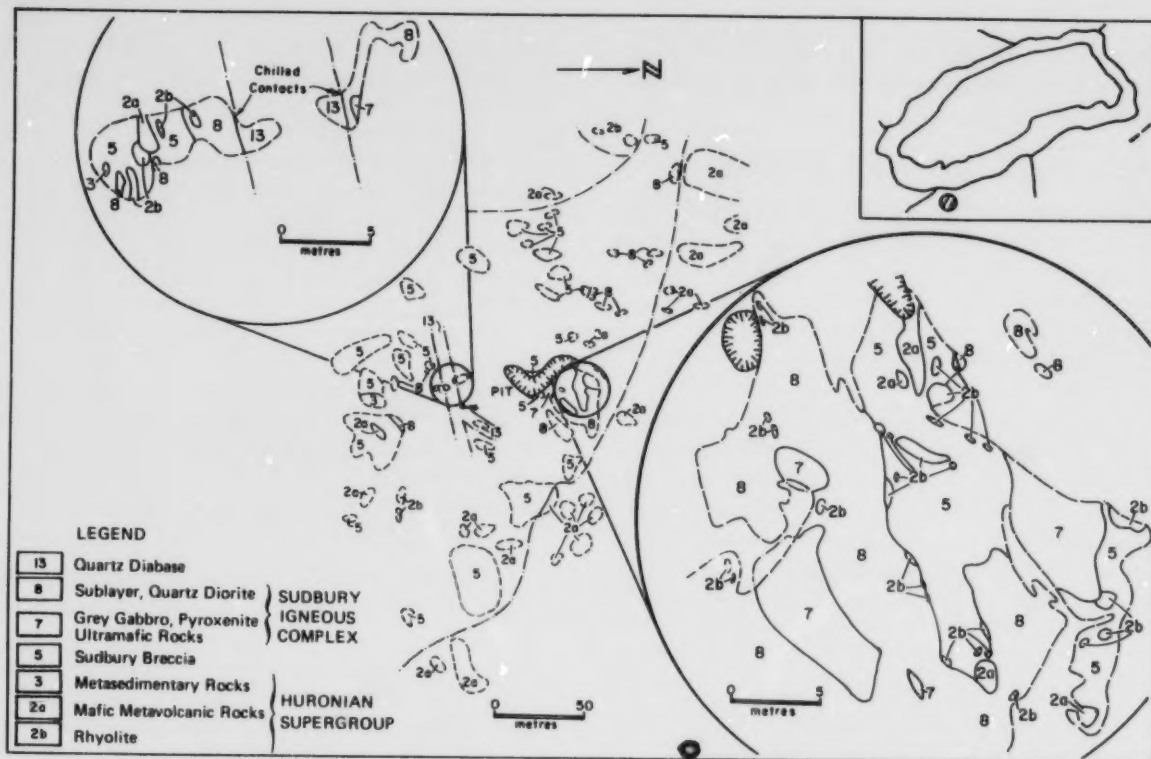


Figure 12.8. Vermilion Area. Detailed Geology.

4. Contacts between quartz diorite and breccia are sharp. Spherulitic textures and slight decreases in grain size are common at the quartz diorite margins, but these do not have definite chilled margins such as those displayed by quartz diabase dikes.
5. Xenoliths of country rock and exotic rocks occur within the quartz diorite, and many of them straddle the contact between the quartz diorite and the adjacent Sudbury Breccia.
6. Sulphides generally occur as ubiquitous blebs and massive bodies preferentially located within the central parts of dike segments, and as massive and disseminated angular to rounded sulphides in breccia associated with quartz diorite pods.
7. Some quartz diorite pods contain 2 or perhaps more, delicately interfingering types of texturally distinct quartz diorite.
8. Irregularly shaped feldspar-rich xenoliths are present in most quartz diorite.

Discontinuous Quartz Diorite Occurrences

MACLENNAN

The quartz diorite in MacleNNan Township is an irregularly shaped body up to 900 m wide which narrows

with depth. It lies within a zone of massive, variably recrystallized Sudbury Breccia. The Offset dike is separated from the Main Mass by up to 300 m, and has apparently no connection with it. The body is texturally and mineralogically heterogeneous and has undergone such intense crushing, shearing, and alteration that comparison with other bodies is difficult. Some of the varieties of quartz diorite present appear similar to quartz granophyre-rich types observed in the Manchester Offset Dike. Most of the sulphides occur as irregular lenses within Sudbury Breccia at the southwestern contact of the quartz diorite body. The quartz diorite itself is barren except for a pod that occurs within sheared xenolith-rich sulphide.

CREIGHTON

Pattison (1979) described the Creighton Embayment as "a trough-like depression in the South Range foot-wall that extends downward for at least 3 km... Most of the embayment is filled with sulphide and inclusion-bearing quartz-rich irruptive (Sudbury Igneous Complex) norite. The sublayer rocks occupy the margins of the trough as an irregular branching sheet up to 150 m thick..." Quartz diorite is a minor rock type in this Sublayer sheet and is largely confined to the deeper

parts. A partly mineralized dike of quartz diorite intrudes the Footwall rocks for several hundred m.

PETROGRAPHY

Pattison (1979) discussed the Sudbury Sublayer at some length. The present study is confined to quartz diorite, the commonest facies of the Sublayer. The other Sublayer rocks are described by Naldrett *et al.* (Chapter 11, this volume) and are compared to quartz diorite in some environments. Lower Zone Sudbury Igneous Complex rocks, which are used for comparison with quartz diorite in the section on "Geochemistry", have been described in detail by Naldrett *et al.* (1970) and are described in this volume by Naldrett and Hewins in Chapter 10. On the basis of occurrence and mineralogy, quartz diorite may be divided into 3 broad groups: main dike, offset contact, and contaminated varieties. The character and occurrence of offset dike rocks are summarized in Table 12.1.

Main Dike Quartz Diorite

The 3 recognized types of main dike quartz diorite, named after the dominant mafic mineral present, are: (1) hypersthene, (2) pyroxene, and (3) amphibole-biotite quartz diorite.

Hypersthene quartz diorite consists of medium- to coarse-grained acicular hypersthene and usually smaller laths of plagioclase, with interstitial quartz, orthoclase, granophyric intergrowth of quartz and orthoclase, and biotite (Photo 12.1). Quartz plus orthoclase content is 7 to 15%. Accessory minerals are apatite, sphene, leucoxene, and ilmenite. Small radioactive haloes are common within biotite, in most cases surrounding grains of sphene, and less commonly sur-

rounding grains of zircon. Many hypersthene grains are rimmed by green pleochroic amphibole. Epidote and scapolite are alteration minerals generally associated with plagioclase.

Pyroxene quartz diorite is similar in most respects to hypersthene quartz diorite, but most of it is finer grained and contains blocky, commonly twinned, clinopyroxene in addition to hypersthene (Photo 12.2). The overall mafic content of pyroxene quartz diorite is slightly higher than hypersthene quartz diorite and its hypersthene is less acicular. Where observed, the contact between hypersthene and pyroxene quartz diorite appears gradational over a distance of a few m.

Amphibole-biotite quartz diorite is the most common variety (Photo 12.3). It is the principal type in the radial offset dikes and, generally, is the major Sublayer rock in the parallel dikes. In most cases, it is medium grained and texturally subophitic to equigranular. Most of the amphibole and biotite is pseudomorphic after pyroxene, which suggests that this variety of quartz diorite results from alteration of either or both of hypersthene and pyroxene quartz diorite. Main dike quartz diorite varieties differ principally in pyroxene content and degree of pyroxene alteration.

Offset Dike Contact Quartz Diorite

Biotite quartz diorite is a common contact rock in the offset dikes. It is usually fine grained to very fine grained, and consists of subhedral blocky plagioclase, equigranular biotite, and interstitial quartz with or without granophyre and minor amphibole. Accessory minerals are essentially the same as in the main dike varieties; some of the biotite is altered to chlorite. Contacts between biotite quartz diorite and the main dike varieties are sharp or sharply gradational. The

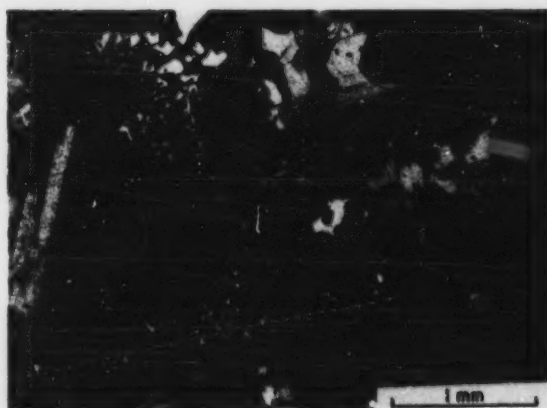


Photo 12.1. Hypersthene quartz diorite, Copper Cliff North Mine C723348, crossed nicols. This type of quartz diorite is characterized by medium to coarse grain size and the acicular habit of the pyroxene and plagioclase. The interstices are filled with quartz, granophyre, and orthoclase.

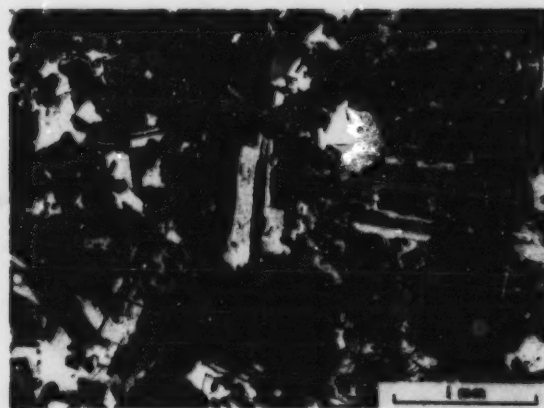


Photo 12.2. Pyroxene quartz diorite, Copper Cliff North Mine C760432, crossed nicols. Pyroxene quartz diorite is a fresh, unaltered version of amphibole-biotite quartz diorite. Pyroxene, largely hypersthene, is medium grained, blocky to prismatic.

contacts with the breccia, however, appear gradational, owing to similarities of mineralogy and fine grain size.

The development of biotite quartz diorite as a contact phase can be attributed to alteration or assimilation of siliceous country rock material, or a combination of these processes. Absence of textural evidence for alteration leads us to the tentative conclusion that the mineralogy and texture of the contact phase of the quartz diorite result from assimilation.

A different type of quartz diorite occurs along some contacts and also between main dike varieties. It is commonly spherulitic in texture and consists of radiating clusters of lathy plagioclase and green amphibole which is pseudomorphic after hypersthene. Quartz, granophyric quartz and orthoclase, and biotite occur interstitially, together with accessory minerals similar to those in the main dike varieties. This spherulitic quartz diorite appears to be a quenched rock which cooled rapidly against the country rock. It is particularly well developed at the margins of quartz diorite pods in the parallel offset dikes.

Contaminated Quartz Diorite

At the MacLennan Mine and the Manchester Offset Dike, 2 unusual varieties of quartz diorite are recognized:

1. The granophyric variant is medium to coarse grained and consists of subhedral or euhedral plagioclase crystals commonly rimmed with granophyric quartz and orthoclase, blocky amphibole grains, quartz, biotite, and sphene.

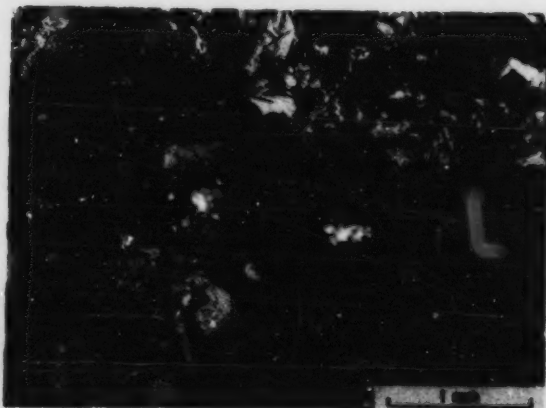


Photo 12.3. Amphibole-biotite quartz diorite, Copper Cliff South Mine C800334, crossed nicols. This type of quartz diorite is the common variety in most major offset dikes. The rock is medium grained and subdiabasic to equigranular in texture. The mafic minerals are biotite and amphibole, which often appear to be pseudomorphous after pyroxene. Plagioclase is lathy to subhedral, and quartz is present interstitially in varying amounts.

2. A quartz-rich quartz diorite, that is similar to, but usually finer grained, than the granophyric variety, that contains much interstitial quartz, and has much less granophyric quartz and orthoclase. Biotite, hornblende, and chlorite comprise the remainder of the latter variety.

In the Manchester Offset Dike, the granophyric quartz diorite occupies the core of the dike, and the quartz-rich variety occurs on either side of it in sharp contact with the country rock. These varieties are thought to be the result of the assimilation of siliceous Huronian metasedimentary rocks.

Distal Copper Cliff Offset Dike Diorite

Quartz diorite in the distal part of the Copper Cliff Offset Dike (see Figure 12.4) is chemically, mineralogically, and texturally distinct from the other quartz diorites. The amphibole is lathy, blue-green to brownish, and twinned, and is probably pseudomorphic after pyroxene. Exsolved opaque minerals are common along relic pyroxene cleavage planes within amphibole. Plagioclase grains are blocky to prismatic and appear dirty in unpolarized light. Most of them are altered at their cores. Granophyric quartz and orthoclase intergrowths, and minor mono-mineralic quartz and orthoclase occur interstitially, and in total represent about 10% of the rock. Biotite is absent. Chlorite, epidote, and carbonate are minor secondary minerals. Opaque minerals, constituting 1 to 2% of the rock, occur as skeletal grains. Although, as will be described below, these rocks are olivine normative, modal olivine or olivine pseudomorphs are absent. It is possible that olivine did crystallize early and was resorbed during pyroxene crystallization. The colour of the amphibole, the oxide content, the absence of biotite, and the low quartz content make this rock petrographically unique among offset-filling quartz diorites.

Sulphide Minerals

Pyrrhotite, chalcopyrite, and pentlandite are ubiquitous in Sudbury quartz diorites where these sulphides range from very minor disseminations to ore grade concentrations. The sulphides most commonly occur as small (> 1 cm), elliptical blebs which produce a characteristic rusty spot pattern on weathered outcrops. Some of these blebs have a rim of amphibole or chlorite; others appear elongated or deformed and are rimmed with biotite and epidote. Major concentrations of sulphide, commonly occurring as subvertical, pipe-like bodies, are almost entirely restricted to main dike quartz diorites. There are no obvious mineralogical differences between sulphide-bearing and non-sulphide-bearing phases of quartz diorite (Souck, Podolsky *et al.* 1969).

Xenoliths

Xenoliths occur in the offset dikes in amounts up to 90%. Two types are recognized: country rock and exotic. The country rock xenoliths consist of locally derived metavolcanic, metasedimentary, and granitoid rocks, gabbro, and anorthositic rocks. The xenoliths are angular to subrounded, and range in size from microscopic to 10s of m in diameter. The exotic xenoliths range in composition from 2-pyroxene gabbro to ultrabasic rocks (Souch, Podolsky *et al.* 1969). These xenoliths are usually well rounded and range in size from a couple of mm to more than 50 m. Pattison (1979) noted that concentration of exotic xenoliths varies directly with the abundance of sulphides; a feature that suggests a genetic link.

Angular to subangular xenoliths, up to several cm in diameter, and of a variety of compositions, occur with minor disseminated sulphides as clusters within quartz diorite (Photo 12.4). In some localities, such as in the Copper Cliff and Worthington Offset Dikes (see Figures 12.4 and 12.5), these xenoliths are in a fine-grained quartz diorite matrix that is itself in sharp contact with the quartz diorite of the main dike. The fine-grained quartz diorite matrix is mineralogically and texturally very similar to the main dike quartz diorite. This similarity and the field relationships suggest that the 2 are probably comagmatic, but the inclusion-bearing quartz diorite inclusion is an earlier crystallized phase which has been brecciated.

At Vermilion (see Figure 12.8), a medium-grained amphibole-biotite quartz diorite occurs as very irregular inclusions within fine-grained amphibole-biotite quartz diorite. A similar situation has been observed in the Copper Cliff Offset Dike, except that in this case, the included rock is fine-grained quartz diorite and the host rock is medium-grained quartz diorite.

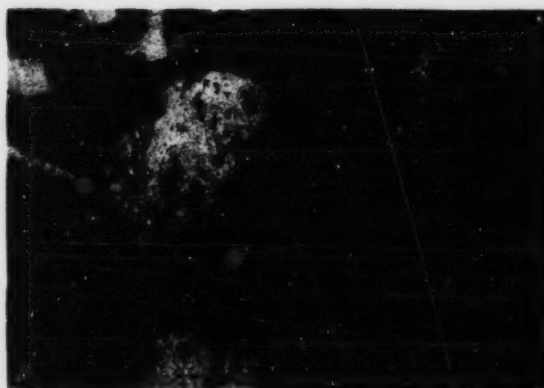


Photo 12.4. A cluster of mafic inclusions in quartz diorite which is itself an inclusion within quartz diorite of the Worthington Offset Dike.

These relationships suggest that the cooling history of quartz diorite was complicated.

Small feldspathic xenoliths, usually < 2 cm in diameter, are ubiquitous. Their irregular, highly embayed edges suggest that they were extensively corroded and heated by the quartz diorite magma; in some cases, they may have approached the melting temperature. Concentrations of these inclusions occur in some locations (Vermilion, Worthington), but for the most part they are widely scattered. In a few cases, larger feldspathic xenoliths (10 to 15 cm diameter) have been observed to be deeply embayed by fingers of quartz diorite (Photo 12.5). The invading quartz diorite is slightly finer grained than quartz diorite hosting the xenoliths.

Relationship with other Rocks of the Sudbury Igneous Complex

The occurrence of quartz diorite and of the other Sub-layer rocks that are closely associated spatially and genetically with quartz diorite offset dikes are shown in Table 12.1.

Where the offset dikes are in contact with the Main Mass of the Sudbury Igneous Complex on the South Range, the contacts between quartz diorite and the basal quartz-rich norite appear to be gradational. The quartz-rich norite is a medium- to coarse-grained rock with a subophitic, locally lineated texture. Mineralogically, it is very similar to amphibole-biotite quartz diorite, but differs in terms of texture and mineral habit. In many places, the basal quartz-rich norite contains country rock xenoliths and disseminated sulphides. It occurs within embayment structures and along the base of the Main Mass; it also occurs as xenoliths ranging in size from microscopic to a few m in



Photo 12.5. A feldspathic inclusion embayed by fingers of quartz diorite. Quartz diorite intruding the fragment is slightly finer grained than the quartz diorite hosting the fragment (Vermilion Offset Dike).

diameter within the Worthington and Copper Cliff Offset Dikes.

"Pyroxene Sublayer" is a medium-grained norite consisting predominantly of lathy, subhedral, poorly zoned plagioclase, prismatic orthopyroxene, and lathy to prismatic clinopyroxene. It underlies parts of the Main Mass. In most parts of the North Range, "pyroxene Sublayer" is in contact with mafic norite, but on the South Range it underlies basal quartz-rich norite. Within embayment structures, it occupies a position between main dike quartz diorite and the Main Mass.

Quartz Diabase

Quartz diabase (in part, the trap dikes of Card (1968), Cooke (1946), and others) occurs as narrow, usually discontinuous, east-striking, near vertical dikes. It is often mistaken for quartz diorite because it has similar appearance, mineralogy, and chemistry. Quartz diabase consists of green amphibole (pseudomorphic after pyroxene), plagioclase, biotite, quartz, and oxides. Its quartz content is generally lower than that of quartz diorite, and its oxide content higher. Quartz diabase only rarely contains granophyric intergrowths of quartz and orthoclase, although myrmekite is common.

Crosscutting relationships indicate that the quartz diabase dikes are younger than the Sudbury Igneous Complex (1849 Ma, Krogh *et al.* 1982) and the quartz diorite, but are older than the Sudbury Swarm diabase dikes (1460 ± 130 Ma, Gates and Hurley 1973). Cooke (1946) suggested that they were emplaced shortly after the intrusion of quartz diorite, but before the tectonic adjustment of the Main Mass. He thought that they might be related to gabbroic sills that occur at the contact between the Onwatin and Chelmsford Formations.

GEOCHEMISTRY OF QUARTZ DIORITE OFFSET DIKES

Although much has been written about the chemistry of the Sudbury Igneous Complex norite and micropegmatite, little geochemical work has been done on the offset dikes since the work by Collins (1934). In the present study, whole-rock analyses were made of 114 surface samples of quartz diorite from the South Range and 19 from the North Range. The objectives were to check for chemical evidence of differentiation or assimilation of country rock inclusions by noting compositional variations across and along the strike of the offsets, and to compare the chemical composition of the quartz diorite with the rocks of the Main Mass of the Sudbury Igneous Complex. Sample locations are shown in Figures 12.4 and 12.5. Sulphides were

avoided in the sampling, but in most cases, it was impossible to completely exclude them. Weathered material, sulphide, and visible xenoliths were removed as much as possible by diamond sawing prior to analysis. Most samples were free of xenoliths or contained much less than 5% xenolithic material by volume when submitted for analysis. All samples were analyzed by XRF-fusion whole-rock techniques; approximately 1/3 of the samples were analyzed for Na_2O by atomic absorption spectrophotometry.

Samples of Lower Zone Sudbury Igneous Complex norite from Blezard and Wisner Townships were also collected for comparison; Blezard samples were analyzed as described above; Wisner samples were analyzed by XRF-fusion whole-rock techniques at Laurentian University. As in the case of quartz diorite sampling, care was taken to avoid sulphides, alteration, and inclusions.

Analytical results for the detailed sampling traverse made near the eastern margin of the Copper Cliff Offset Dike south of Copper Cliff North Mine (see Figure 12.4) are shown in Figure 12.9. Here, the offset is 60 m wide and consists of quartz diorite with a minor proportion of xenoliths of quartz-rich norite in sharp contact with medium-grained granite. A total of 8 samples were taken along a line normal to the contact. The first 2 samples, which were taken at 1 and 3 m from the contact, are appreciably higher in SiO_2 , Al_2O_3 , and K_2O , and lower in Fe_2O_3 and TiO_2 than the remainder of the samples taken well away from the

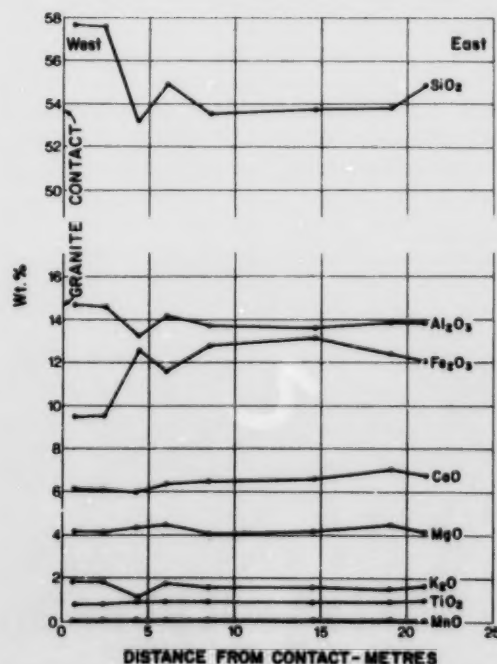


Figure 12.9. Copper Cliff Offset Dike. Detailed Traverse Oxide Variations.

contact, and clearly showing the influence of the assimilation of granitic material.

Additional samples were taken at 4 separate locations of the Copper Cliff Offset Dike along its length. These results are presented in Figure 12.11. The samples were collected both near the contact with the country rock and within the dike away from the contact. In every case, the samples taken at or near the contact show a corresponding enrichment or depletion, relative to the sample taken away from the contact, in those elements which are abundant or lacking in the adjacent country rock. For example, in the case of the 2 samples taken at a distance of 8.4 km from the mouth of the embayment, the sample taken 0.3 m from the contact is enriched in SiO_2 and K_2O , and depleted in Fe_2O_3 , Al_2O_3 , CaO , MgO , MnO , and TiO_2 relative to the sample taken in the mid-part of the dike. This relationship would suggest that the near-contact rock is contaminated with the adjacent country rock, which is feldspathic quartzite. Similarly at 9.6 km from the mouth, where the offset dike is in contact with a Sudbury gabbro sill, samples taken 0.6 and 0.3 m from the contact, like the sill, are richer in CaO , MnO , Al_2O_3 , and lower in SiO_2 , Na_2O , K_2O , and Fe_2O_3 than the sample taken 3 m away. The magnitude of oxide variations is much less here than in the previous case (where the adjacent country rock was feldspathic

quartzite). This is compatible with the precept that basic magma cannot assimilate much rock of similar basic composition.

A sampling traverse was also made across the eastern limb of the Worthington Offset Dike (see Figure 12.5). Here the offset is about 310 m wide and consists primarily of quartz diorite with minor indistinct xenoliths of basal quartz-rich norite. On its western side, the dike is in sharp contact with coarse-grained amphibolite; on its eastern side, it is in contact with feldspathic quartzite. The chemical variation is shown in Figure 12.10. From west to east, the dike rocks show a relative gain in SiO_2 , Na_2O , and K_2O , and a corresponding loss in MgO , Fe_2O_3 , and CaO , and no net change in TiO_2 , Al_2O_3 , and MnO . These changes are what would be expected if the proportion of assimilated feldspathic quartzite increased toward the contact. The effect of this assimilation is apparent even in the middle of the offset dike, a distance of approximately 150 m. Slight enrichment in MgO , CaO , and Fe_2O_3 near the western margin relative to the mid-parts of the dike suggest very minor contamination of quartz diorite by mafic material. This is consistent with the concept that assimilation is dependent on the degree of melting of the rock being assimilated. Granite or feldspathic quartzite are composed of low melting point minerals and will be assimilated to a greater degree by quartz diorite magma than amphibolite or gabbro, which are composed of higher melting point minerals.

The above examples illustrate that assimilation occurred and changed the quartz diorite composition. These examples indicate in particular that assimilation is pronounced near offset dike contacts and can be directly related to the composition of adjacent country rock.

The sampling along the length of the Copper Cliff Offset Dike was intended to determine what, if any, compositional variations occurred along strike in these bodies. The results are presented in Figure 12.11. The sampling density is somewhat uneven and subtle changes in composition may have been missed. Over a strike length of 14 km, however, certain gross variations are apparent.

The most notable feature is the difference between the proximal part of the offset dike, up to 9 km, and the distal part, from 9 to 14 km from the mouth of the embayment. The distal part is more mafic, and on average it is much lower in SiO_2 and higher in Al_2O_3 , TiO_2 , MgO , and CaO . Because of the low sampling density and because of faulting of the offset dike, it is not possible to say whether the change is gradational or abrupt. The change does, however, occur over a distance of < 1.2 km, which is the apparent displacement of the fault separating the 2 sample locations. The distal part, as we shall see later, is compositionally distinct from the proximal parts of all of the other South Range Offset Dikes analyzed. As the distal parts of

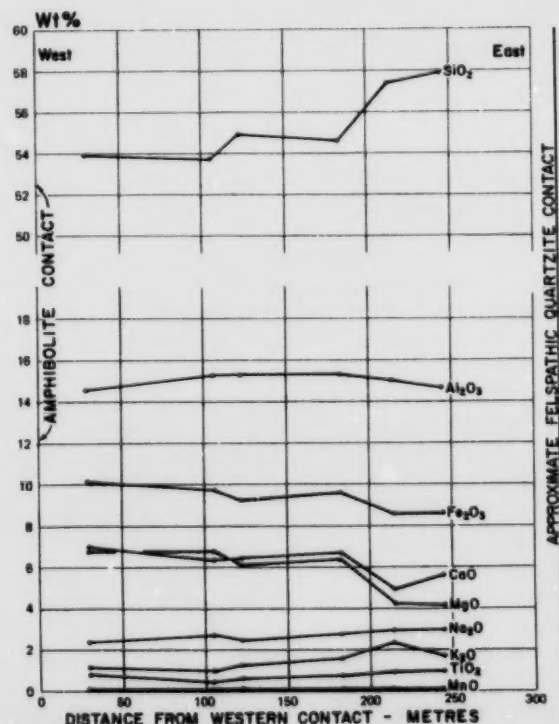


Figure 12.10. Worthington Offset Dike. Detailed Traverse Oxide Variations.

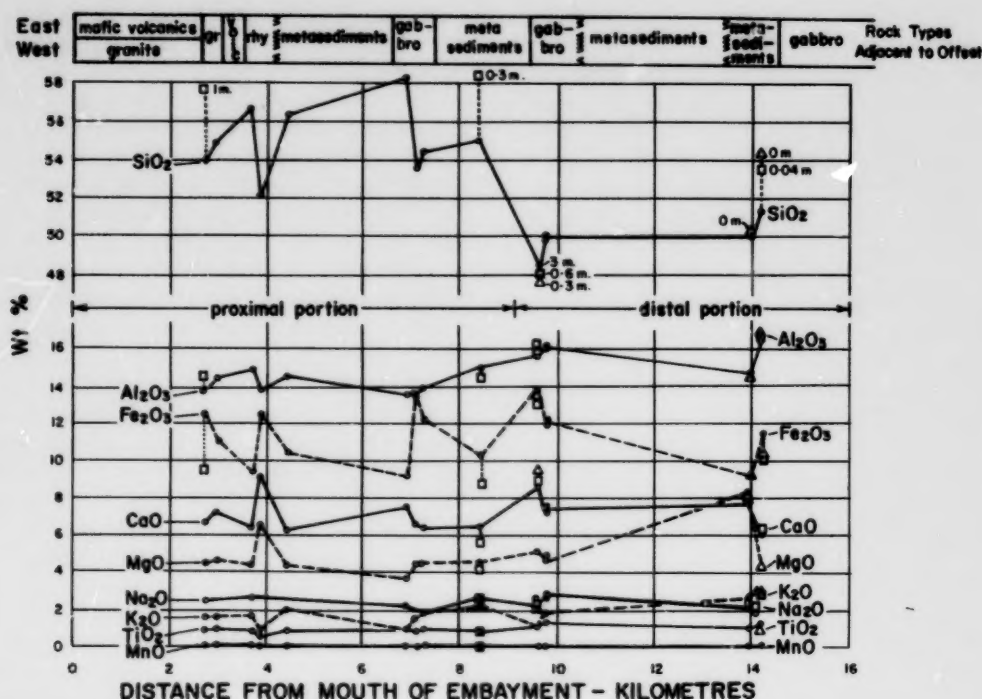


Figure 12.11. Copper Cliff Offset Dike. Compositional Variations Along Strike.

other offset dikes have not been sampled, it is not known whether the distal part of the Copper Cliff Offset Dike is unique among the distal parts of offsets or not.

Considered separately, the compositional variations within the proximal and distal parts of the offset dike can be accounted for by assimilation. The largest change between samples along strike is of the same magnitude as the change between samples across the dike. There does not appear to be a discernible non-contamination related trend of compositional variation along either the proximal or distal parts of the dike.

Both limbs and the main part of the Worthington Offset Dike were also sampled along strike (see Figure 12.5); the observed compositional variations are shown in Figure 12.12. Over the distance sampled, there are no marked changes in composition along strike as observed in the Copper Cliff Offset Dike. At Worthington, the compositional changes are slight and gradual with respect to most oxides. SiO_2 , Al_2O_3 , K_2O , and TiO_2 increase, while MgO , Fe_2O_3 , MnO , and CaO slightly decrease with distance from the Main Mass of the Complex. Since only the first 8 km of the offset dike nearest the Main Mass was sampled, it is possible that farther along strike, there may be a compositionally distinct distal part. The eastern and western limbs are remarkably similar in composition over equivalent strike length and distance from the Main Mass.

These gradational compositional changes could

have resulted from either differentiation, or the cumulative effects of assimilation. If any differentiation has taken place, it appears to have been only minor, based on the data on hand. Assimilation is clearly the major cause of compositional variation.

Affinities to Sudbury Igneous Complex Rocks

In view of the physical association and petrographic similarities between quartz diorites and the noritic rocks of the Sudbury Igneous Complex, it might be expected that they would also be chemically similar. Average compositions presented in Table 12.2 confirm this expectation. Average values for quartz diorite are based only upon relatively unaltered samples. The Sudbury Igneous Complex Main Mass average compositions are based on all available samples of the relevant units. These samples were not petrographically selected as in the case of the quartz diorites. The variability of the Main Mass average compositions probably results in part from alteration and/or the presence of xenolithic material.

Average composition of the Worthington and proximal Copper Cliff Offset Dikes (Table 12.2, columns 1 and 2) demonstrate their chemical similarity. The weighted average of these 2 averages, shown in column 3, is assumed to represent South Range quartz diorite; it is intermediate between the composition of

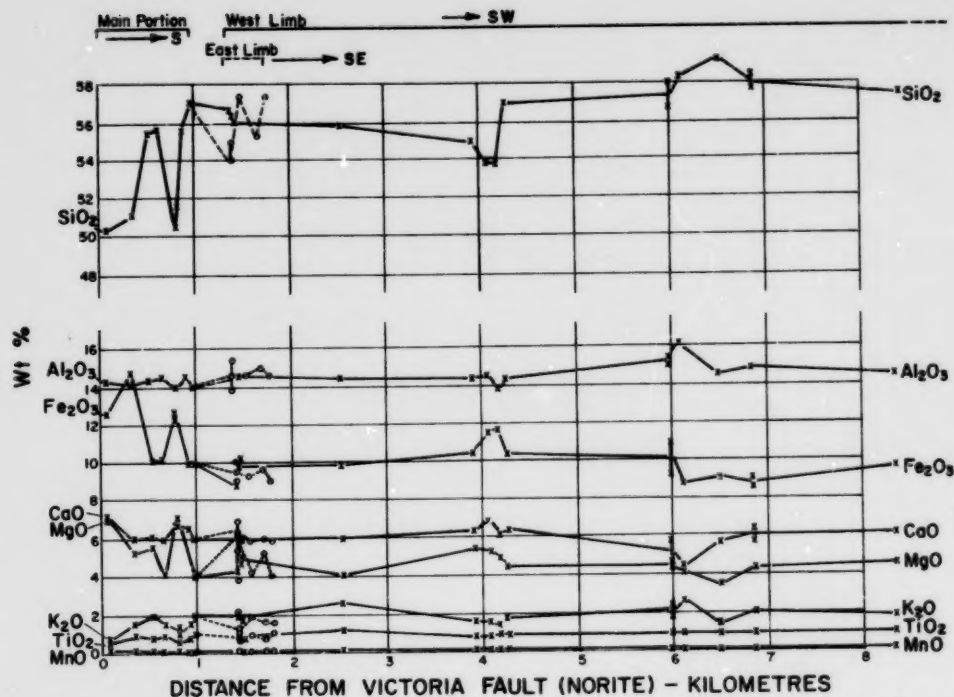


Figure 12.12. Worthington Offset Dike. Compositional Variations Along Strike.

the South Range norite and quartz gabbro shown in columns 7 and 8, respectively. With respect to SiO_2 , however, and to a lesser extent CaO , the South Range quartz diorite is more similar to quartz-rich norite (column 6). For all oxides, except TiO_2 , South Range quartz diorite values are within 1 standard deviation of the South Range quartz gabbro mean value. Distal Copper Cliff Offset Dike quartz diorite (column 4) is also intermediate in composition between South Range norite and quartz gabbro for the most part, but SiO_2 is much lower, and K_2O higher, than in any of the indicated Sudbury Igneous Complex Main Mass rocks.

North Range quartz diorite, represented by the average of samples from Ministic, Foy, and Whistle Offsets Dikes (column 5), is higher in SiO_2 , Al_2O_3 , K_2O , and Na_2O , and lower in Fe_2O_3 , MgO , CaO , TiO_2 , and MnO than that of the South Range. Except for Al_2O_3 , these differences are similar to those between North Range and South Range quartz gabbro. The variations in composition of samples from the 3 North Range offset dikes are smaller than that for samples from South Range offset dikes. This results from the generally lesser alteration of North Range rocks and confirms the similarity of quartz diorite from widely separate locations. North Range quartz diorite is very similar in composition to felsic norite (column 9), except that it is much lower in CaO and much higher in K_2O .

Average normative mineral compositions, also

given in Table 12.2, show that the North Range quartz diorite has plagioclase with a lower An content, less pyroxene, and more quartz and orthoclase than South Range quartz diorite, and is, therefore, more differentiated. North Range quartz diorite is also slightly more differentiated than either felsic norite or quartz gabbro. Both North and South Range quartz diorite are actually quartz monzodiorites since normative orthoclase constitutes 20 to 35% of the total feldspar content. North Range samples are transitional into granodiorite as defined by IUGS (1973). The distal Copper Cliff offset rocks are in part olivine monzodiorites (olivine-normative). They are less differentiated than any of the other rocks shown and do not appear to have an analogue within the Main Mass of the Sudbury Igneous Complex.

In a general sense, quartz diabase is compositionally intermediate between South Range quartz diorite and distal Copper Cliff diorite.

AFM and CFM diagrams in Figure 12.13 illustrate the intermediate nature of quartz diorite between quartz gabbro and norite of the South Range, and between quartz gabbro and felsic norite of the North Range. The North Range Wisner rocks lie on either side of the line dividing tholeiitic and calc-alkalic fields on the AFM diagram. North Range quartz diorites show an alkali enrichment trend, whereas South Range quartz diorite exhibits an iron-enrichment trend. The iron-enrichment trend for South Range quartz diorite

TABLE 12.2: AVERAGE COMPOSITION (X) AND VARIABILITY (δ) OF SAMPLES FROM VARIOUS OFFSET DIKES AND SUDBURY IGNEOUS COMPLEX ROCKS.

	1	2	3	4	5	6	7	8	9	10	11
	X	X	X	X	X	X	X	X	X	X	X
	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)
SiO ₂	56.9	55.3	56.0	50.7	61.5	56.7	53.7	54.3	60.4	58.9	54.0
Al ₂ O ₃	14.8	14.3	14.5	16.3	14.9	16.3	17.8	14.7	15.6	13.5	13.8
Fe ₂ O ₃	10.5	12.0	11.3	12.7	7.60	8.27	7.78	12.1	7.99	11.7	13.5
MgO	4.76	4.43	4.57	4.91	3.82	4.46	6.83	3.68	3.81	2.66	4.29
CaO	6.24	6.71	6.50	7.92	6.61	6.66	7.80	7.01	6.05	5.48	7.39
K ₂ O	1.74	1.70	1.72	1.66	0.38	2.60	0.96	1.58	1.96	2.13	1.24
TiO ₂	0.88	0.94	0.91	1.56	0.08	0.73	0.38	2.16	0.65	1.62	1.46
Na ₂ O	2.57	2.61	2.59	2.76	0.20	3.15	-	-	3.12	3.13	2.88
MnO	0.14	0.15	0.15	0.17	0.02	0.11	0.12	0.16	0.13	0.14	0.19
TOTAL	98.6	98.1	98.2	96.6	99.1	-	-	-	99.71	99.26	98.75
n	11	14	25	4	17	31	74	49	31	17	3

	1	2	3	4	5	6	7	8	9	10	11
	X	X	X	X	X	X	X	X	X	X	X
	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)	(δ)
Quartz	7.9	7.9	7.9	0	12.9	12.9	12.2	12.2	12.2	10.9	4.58
Orthoclase	10.4	10.4	10.4	10.1	15.6	15.6	11.7	11.7	11.7	12.3	6.78
Albite	22.5	22.5	22.5	23.9	17.1	17.1	26.7	26.7	26.7	26.9	25.1
Anorthite	23.7	23.7	23.7	28.0	18.8	18.8	22.8	22.8	22.8	17.2	21.6
Enstatite	8.3	8.3	8.3	1.52	7.9	7.9	6.9	6.9	6.9	2.2	5.15
Fe-pyroxene	17.7	17.7	17.7	18.9	11.6	11.6	12.3	12.3	12.3	17.4	20.4
Mn-pyroxene	0.3	0.3	0.3	0.3	0.04	0.04	0.2	0.2	0.2	0.3	0.37
Dioptase	7.4	7.4	7.4	9.6	1.6	1.6	5.9	5.9	5.9	9.11	12.5
Forsterite	0	0	0	4.6	0.6	0.6	0	0	0	0	0
Ilmenite	1.8	1.8	1.8	3.0	0.2	0.2	1.4	1.4	1.4	0.1	2.85
An	51	51	51	54	41	41	46	46	46	39	46
Differentiation	40.8	40.8	40.8	34.0	56.2	56.2	50.6	50.6	50.6	50.0	37.2
Index	22.7	22.7	22.7	22.4	22.2	22.2	22.6	22.6	22.6	23.7	19.6
Solidification	25.7	25.7	25.7	18.9	19.4	19.4	18.9	18.9	18.9	19.6	24.8
Index	8.0	8.0	8.0	10.3	4.1	4.1	6.3	6.3	6.3	15.7	13.6
CIPW	0	0	0	5.8	0	0	0	0	0	0	0
Convention	-	-	-	-	-	-	-	-	-	-	-
(hypersthene,	-	-	-	-	-	-	-	-	-	-	-
augite,	-	-	-	-	-	-	-	-	-	-	-
olivine)	-	-	-	-	-	-	-	-	-	-	-

Key

- 1-Worthington Offset Dike amphibole-biotite quartz diorite
- 2-Copper Cliff proximal offset dike amphibole-biotite quartz diorite
- 3-South Range quartz diorite-weighted average of 1 and 2
- 4-Copper Cliff distal offset dike diorite
- 5-North Range quartz diorite (Foy, Ministic and Parkin offsets)
- 6-quartz-rich norite, Bleazard traverse
- 7-South Range norite, Bleazard traverse
- 8-quartz gabbro, Bleazard traverse
- 9-felsic norite, Wisner traverse
- 10-quartz gabbro, Wisner traverse
- 11-quartz diabase (Victoria area-South Range)

Note: All analyses recalculated volatile-free.

these include only least altered, uncontaminated samples

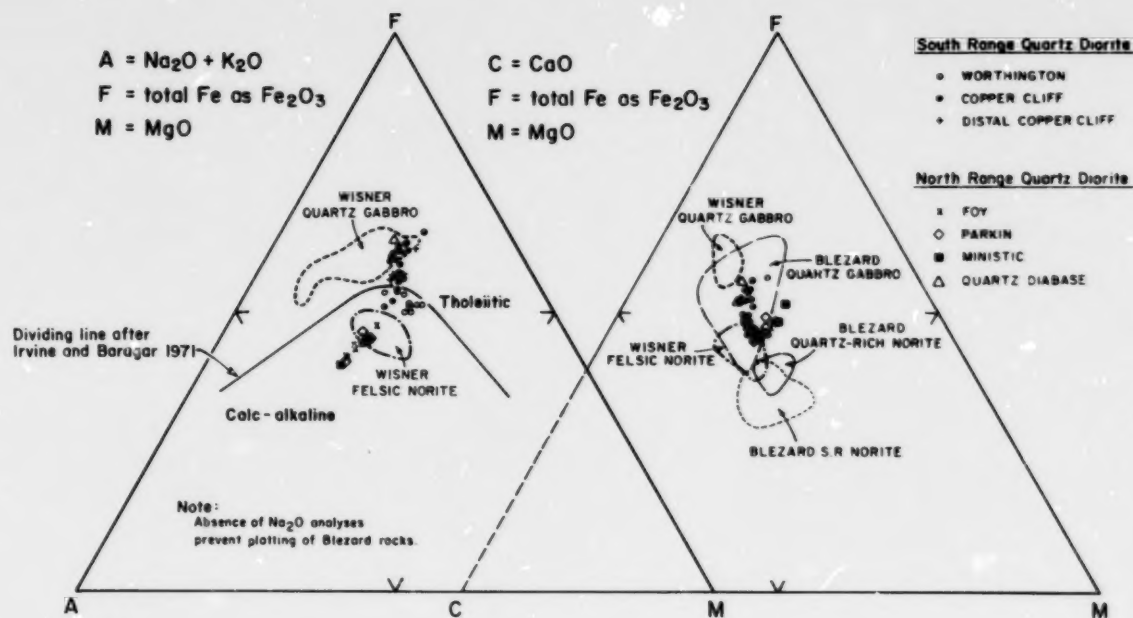


Figure 12.13. Ternary Diagrams—Sudbury Rocks.

is again evident on the CFM diagram. On both the AFM and CFM diagrams, distal Copper Cliff samples plot with proximal Copper Cliff samples, and South Range quartz diabase samples plot very near the Copper Cliff Offset Dike quartz diorite samples.

A plot of Al_2O_3 versus $\text{FeO}/(\text{FeO} + \text{MgO})$ (Figure 12.14) demonstrates a strong linear trend for the entire Sudbury Igneous Complex. The trend passes from the high-alumina basalt field into the tholeiitic field (with gross increase in stratigraphic height within the Main Mass). Again, the intermediate position of quartz diorite is apparent. Distal Copper Cliff Offset Dike samples are more aluminous and have slightly higher $\text{FeO}/(\text{FeO} + \text{MgO})$ ratios than the proximal Copper Cliff Offset Dike samples. Quartz diabase samples plot within the cluster of Worthington Offset Dike quartz diorite samples at one end of the trend.

A molar ratio plot of $\text{Al}_2\text{O}_3/\text{K}_2\text{O}$ versus $\text{SiO}_2/\text{K}_2\text{O}$ in Figure 12.15 shows a strong linear trend. On this diagram, the slope of fractionation lines varies in direct relationship to the plagioclase composition. The strong linear trend here results largely from plagioclase crystallization (Cochrane 1982); but is also influenced by pyroxene crystallization. Except for the Blezard quartz-rich norite, stratigraphically higher (more differentiated) units occupy positions progressively closer to the origin. The extensive overlap of fields probably results in part from alteration. An important feature is the most left position, or most differentiated position of North Range quartz diorite, and the fact that the North Range trend appears to be continuous with the South Range quartz diorite trend. Of perhaps even more significance is the similarity of slope

and overlap of fields between quartz diorite and quartz gabbro and felsic norite. Distal Copper Cliff Offset Dike samples define a separate, albeit parallel trend, further confirming their uniqueness. Quartz diabase samples plot below the trend of the Main Mass norite and quartz gabbro, but appear to lie along the extension of the trend of the South Range quartz diorite samples.

On Figure 12.16, a molar ratio plot of $\text{MgO}/\text{K}_2\text{O}$ versus $\text{FeO}/\text{K}_2\text{O}$, 2 converging trends are apparent: a shallow trend representing quartz gabbro and a steep trend representing norite, quartz-rich norite, and felsic norite. The steeper trend largely results from pyroxene crystallization; the pyroxene atomic $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio predicted by the slope of this trend (0.44) is higher than the range measured by Naldrett *et al.* (1970); where it is 0.27 to 0.38 for both clinopyroxenes. This indicates that the steep trend on Figure 12.16 is influenced by the presence of minor sulphides, iron oxides, and biotite. The shallower, higher iron trend clearly reflects the presence of significant amounts of iron oxides in the quartz gabbro. The North Range quartz diorites form a trend with a slope somewhat intermediate between the norite and gabbro trends. South Range quartz diorite forms quite a more scattered field, with a shallower slope, but is also intermediate between the 2 trends. The North Range quartz diorites are the more differentiated, again occupying a position closest to the origin. Quartz diabase samples plot within the South Range quartz gabbro field apparently along the extension of the South Range quartz diorite trend, which is similar to their position in Figure 12.15.

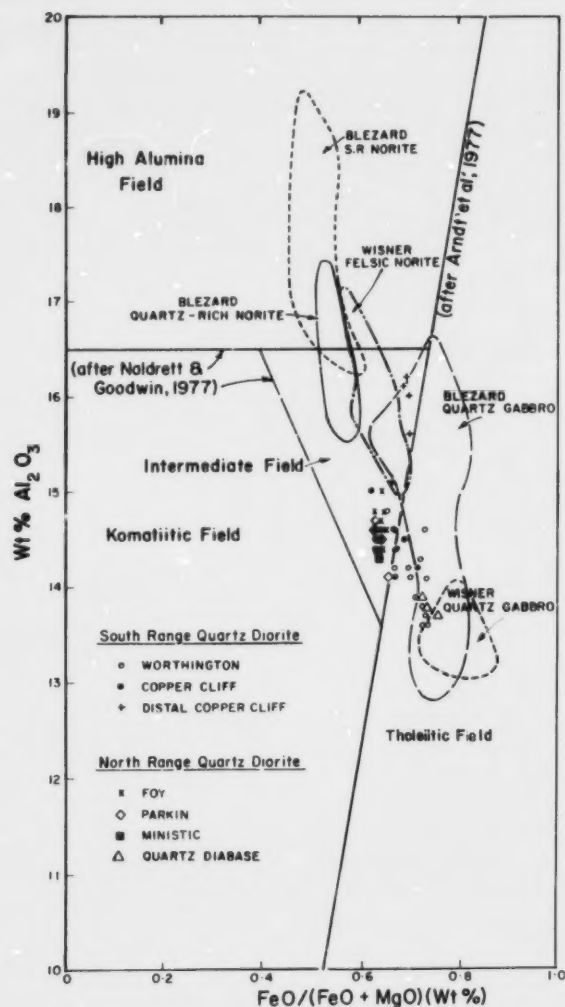


Figure 12.14. Al_2O_3 vs $\text{FeO}/(\text{FeO} + \text{MgO})$ Plot.

DISCUSSION AND CONCLUSIONS

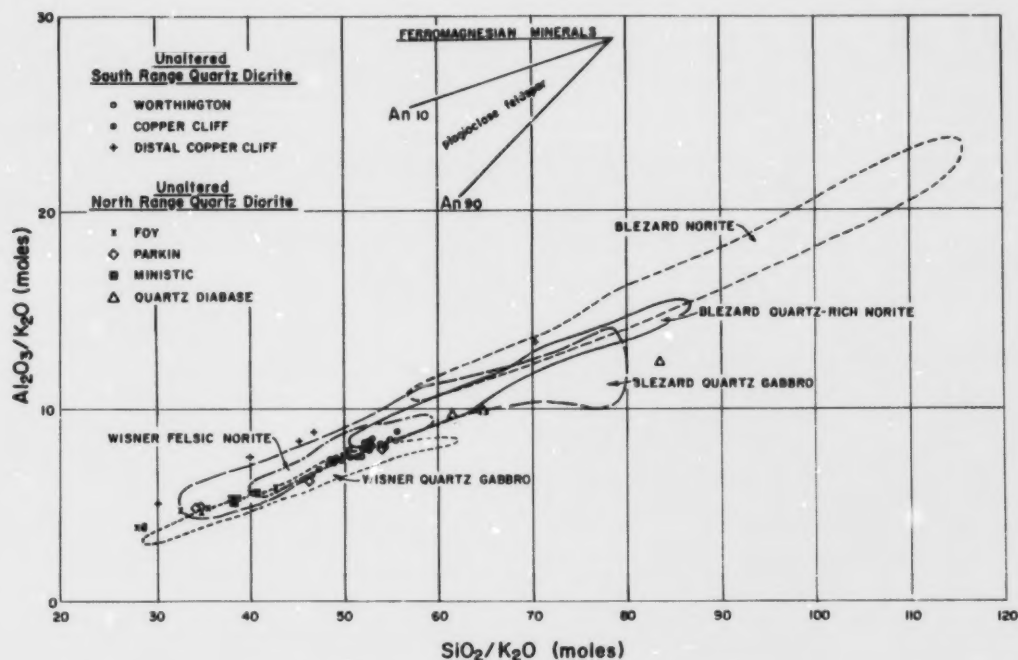
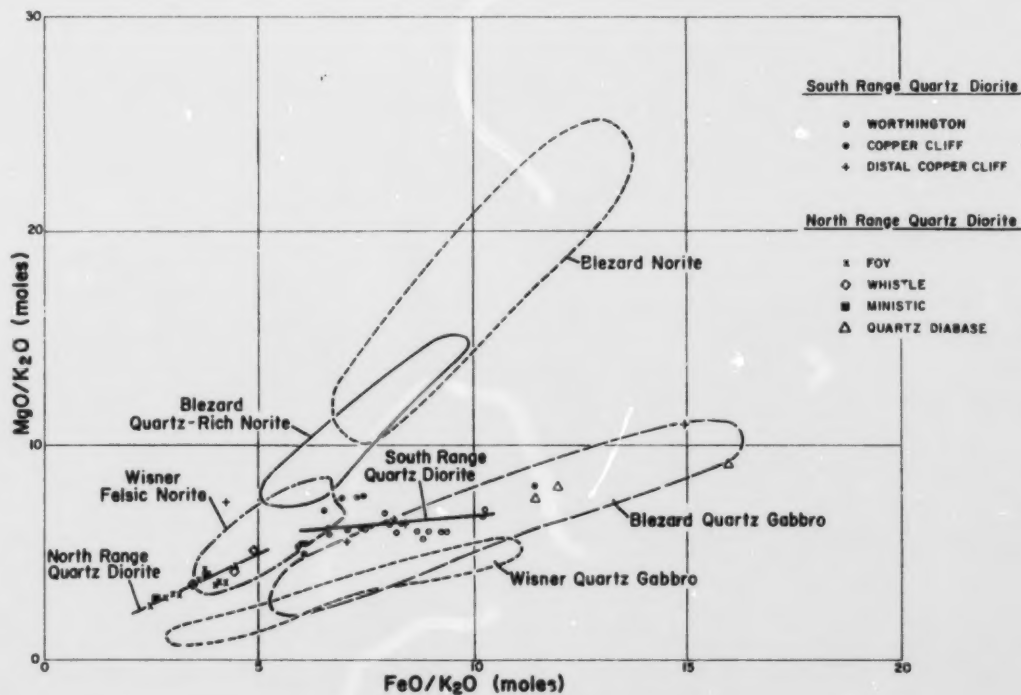
Quartz diorite magma was injected into the variably brecciated Footwall along radial fracture zones extending from the Main Mass of the Sudbury Igneous Complex, and also into unconsolidated breccia zones concentric with the Complex. The radial offset dikes are joined to the Main Mass by large funnel-shaped embayments in the Footwall of the Complex. Quartz diorite, which is the dominant Sublayer rock type at distances of more than about 2 km from the Main Mass, apparently grades from the Sublayer rocks filling the embayments. Sharp, near right angle, changes in strike of the Whistle, Foy, Worthington, and Copper Cliff Offset Dikes suggest the nature of the transition from radial to concentric offset dikes. Consideration of the xenolithic material in the offsets and its source in-

dicates that the direction of movement of magma in the radial offsets was outward from the Main Mass (Pattison 1979). The lack of pronounced chill zones at the offset dike contacts indicates that the country rock was at a high temperature when the quartz diorite magma was injected. Brecciation and heating of the country rock may have resulted from meteorite impact (Peredery and Morrison, Chapter 22, this volume). Injection of the magma was probably triggered by an increase in confining pressure, resulting perhaps from post-cratering tectonic readjustment. The presence of xenoliths of basal quartz-rich norite within the quartz diorite indicates that the quartz diorite is slightly younger than the Lower Zone of the Main Mass. Although this relationship is not in accordance with the model proposed by Pattison (1979), in which the Sublayer pre-dates emplacement of the Main Mass of the Complex, it is in agreement with the contention of Souch, Podolsky *et al.* (1969) that the Sublayer and norite may be contemporaneous.

The magma injected into the Footwall originally crystallized as hypersthene or pyroxene quartz diorite. Subsequently, these rocks were altered to amphibole-biotite quartz diorite, which is presently the most common variety. Assimilation of country rock material has been shown to produce significant changes in quartz diorite composition. Variations along strike in the cores of both the Worthington and the proximal Copper Cliff Offset Dikes are gradual, and in the same sense and of the same magnitude as the assimilation of the siliceous material near the dike margins. No evidence has been found of differentiation within the proximal parts of offset dikes. If this process did operate, then either our sampling interval was too great to detect its effects, or its effects have been obscured by greater effects of contamination.

In the Copper Cliff Offset Dike, an abrupt change in composition occurs between the proximal part, which is typical of South Range quartz diorite, and the more mafic distal part. This difference is apparently not due to contamination, but may reflect differentiation or inhomogeneity of the primary magma prior to intrusion. The former implies that there may have been 2 episodes of intrusion: (1) the intrusion of the mafic distal part and (2) the later intrusion of the proximal part. The paleomagnetic evidence of Morris and Pay (1981) that there were at least 2 offset dike intrusive events, supports this contention.

The average primary oxide and normative mineral compositions of the South Range quartz diorite suggest that it has affinities with the South Range quartz gabbro, and also in some respects is intermediate between norite and quartz gabbro. The North Range quartz diorite is also similar to felsic norite and quartz gabbro, but appears slightly more differentiated than either. The differences between the North

Figure 12.15. Molar Ratio Plot— $\text{Al}_2\text{O}_3/\text{K}_2\text{O}$ vs $\text{SiO}_2/\text{K}_2\text{O}$.Figure 12.16. Molar Ratio Plot— $\text{MgO}/\text{K}_2\text{O}$ vs $\text{FeO}/\text{K}_2\text{O}$.

Range and the South Range quartz diorites are generally similar in kind and degree to the differences between the North Range and South Range quartz

gabbros. This suggests that there is a genetic relationship between quartz diorite and quartz gabbro on each Range.

Various chemical diagrams illustrate the compositional relationship of quartz diorite to quartz gabbro and its similarities to felsic norite. They show also that North Range quartz diorite is more differentiated than South Range quartz diorite. This is perhaps a reflection of the higher stratigraphic position of the North Range relative to the South Range (Souch, Podolsky *et al.* 1969; Naldrett *et al.* 1970). The difference in degree of differentiation implies either, vertical *in situ* differentiation within the quartz gabbro/quartz diorite, or differentiation prior to intrusion. Differentiation prior to intrusion could imply that the quartz gabbro/quartz diorite of the South Range was intruded earlier than that of the North Range. Distal Copper Cliff Offset Dike rocks are believed to represent an early differentiation that was intruded separately.

On the basis of an experimental relationship between MgO and Cu/(Cu + Ni) derived by Rajamani and Naldrett (1978), Pattison (1979) argued that the silicate host rocks of several of the Sudbury orebodies were MgO-deficient. This is also the case for the orebodies hosted by quartz diorite. The coincidence of sulphides with high xenolith populations, which was noted particularly in the central parts of some radial offset dikes, suggests that the sulphides were transported with the xenoliths. These observations suggest that quartz diorite was not the source for the sulphide minerals, but only the transport medium.

The podiform shape of the quartz diorite bodies and the fact that some individual fragments lie across the quartz diorite/breccia boundary in concentric offset dikes suggest that the Footwall Breccia was unconsolidated, and perhaps still tectonically mobile when the quartz diorite magma was injected. Exotic xenoliths and sulphides were carried along by the magma and are presently spatially associated with quartz diorite in Footwall Breccia.

The remarkable similarity in appearance, mineralogy, and composition of the quartz diabase (trap) dikes and quartz diorite may suggest a relationship between them. Crosscutting field relationships, however, indicate that the quartz diabase is younger than the quartz diorite.

Proposed Interpretation

The observations and ideas presented in this study have led the authors to the following interpretation of the origin of the offset dikes. Figures 12.17 and 12.18 are composite, schematic diagrams (not to scale) illustrating in plan and section the geological environments of the various offset dikes. In outline, the interpretation is as follows:

1. Meteorite impact brecciated and heated the Footwall and produced radial and concentric breccia zones.

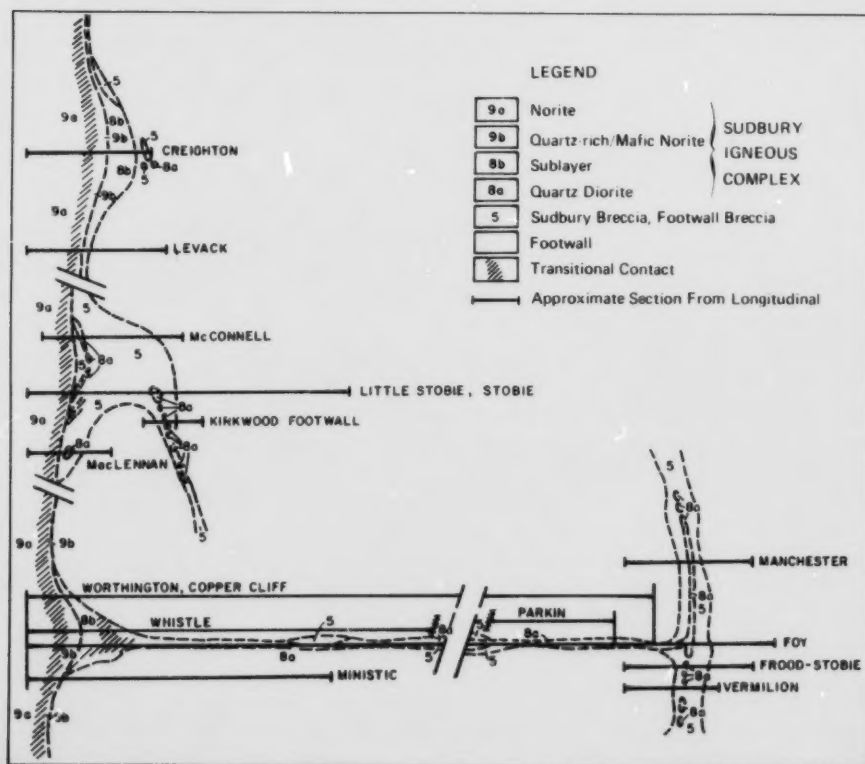


Figure 12.17. Composite schematic plan illustrating conceptual relationships of various offset dike environments.

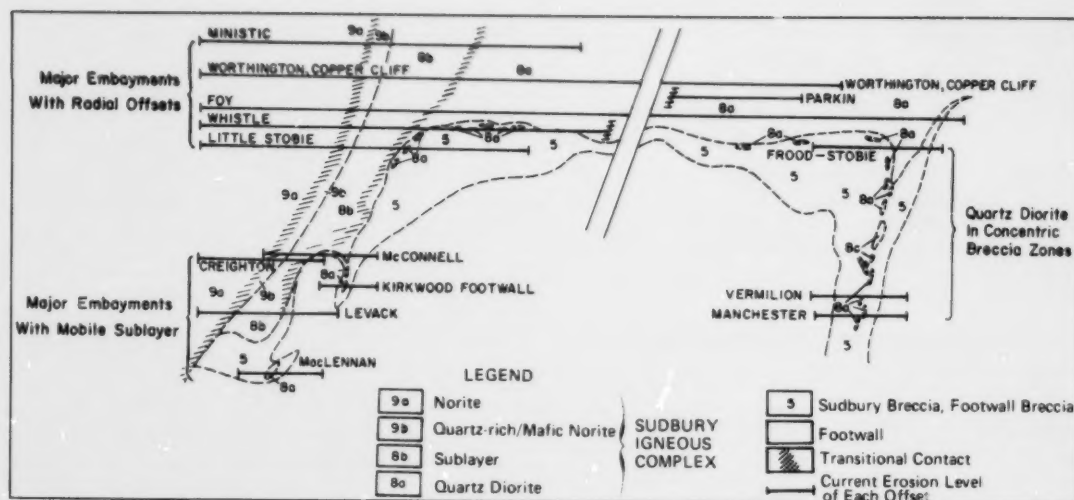


Figure 12.18. Composite schematic section illustrating conceptual relationships of various offset dike environments.

2. The fracturing incurred during meteorite impact permitted magma to intrude beneath the Onaping Formation and fill the lower part of the meteorite crater. Formation of the Main Mass of the Sudbury Igneous Complex began with the crystallization and differentiation of the magma.
3. Later, perhaps as a result of post-impact adjustment, some of the magma was forced into the radial Footwall Breccia zones extending from the crater. This process may have occurred on more than one occasion.
4. As the magma intruded the radial breccia zones, it assimilated the breccia matrix and enveloped the fragments as xenoliths. Assimilation modified the magma composition and flow differentiation concentrated the xenoliths in the centres of the channel ways. The radial offsets were now relatively breccia-poor, having been scoured clean by the flowing magma.
5. Before leaving the Main Mass of the Complex, the quartz diorite magma picked up, possibly from the base of the Complex, sulphides, exotic rocks, and basal quartz-rich norite and carried them as xenoliths into the Footwall.
6. In some areas where the radial breccia zones were not fully developed, magma was injected for only short distances into the Footwall producing aborted offset dikes such as those of Creighton and MacLennan.
7. Magma flowing along a radial breccia zone followed the path of least resistance. If, therefore, a radial breccia zone crossed a concentric breccia zone, the magma could be diverted into the concentric

zone. Where the Copper Cliff Offset Dike intersected the Froid-Sudbury Breccia zone, the quartz diorite magma path continued southward, but in similar circumstances in the Foy and Whistle Offset Dikes, it turned sharply into concentric breccia zones. This process was probably occurring simultaneously in 3 dimensions.

8. Magma was thus injected into the hot, unconsolidated breccia of the concentric zone, which may have been tectonically active at that time. The rounded shape of the quartz diorite pods and sharing of inclusions suggest a surface tension effect prevented the magma from forming a stockwork of veins, and clearly implies that the breccia was unconsolidated at the time.

The above synopsis implies that the quartz diorite magma was derived from the Main Mass of the Sudbury Igneous Complex and is of approximately the same age as the quartz gabbro.

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MINERAL DEPOSITS OF THE SUDBURY IGNEOUS COMPLEX

Ni-Cu Ores of the Sudbury Igneous Complex—Introduction

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INTRODUCTION

The Ni-Cu ores of the Sudbury district are divisible into 5 groups, these are: typical South Range deposits; typical North Range deposits; offset deposits; fault-related deposits; and a miscellaneous group. This miscellaneous group may occur anywhere around the perimeter of the Sudbury Igneous Complex, but for a variety of reasons, which are mainly connected to the group's history subsequent to emplacement, has characteristics that are very different to those of the previous 4 groups. In this introductory section, examples of each of the groups will be described in turn, and special attention will be given to the features common to members of a group. This is done to assist the newcomer to Sudbury geology to come to grips with the very large amount of data that exists about the ore deposits. A truly typical example does not exist for any group; all of the deposits have their individual aspects.

volume), occur in direct and sharp contact with the Footwall rocks. The massive sulphide minerals also have a reasonably well-defined upper contact with a mafic rock, the quartz diorite, which contains up to 60% disseminated sulphide. The proportion of this sulphide decreases steadily upward to 20 to 30%. Some of this ore-type has a blebby, "buckshot" appearance, in which the sulphide minerals form blebs, 5 to 20 mm in diameter, within the quartz diorite matrix. There is usually a rather sharp contact with an overlying norite containing 10% or less sulphide. The sulphide content of the norite decreases upward as the rock grades into the normal quartz-rich norite marginal to the Complex along the South Range. Important features include the presence of inclusions (many of the inclusions are clearly local in origin), and the comparatively unbrecciated nature of the Footwall itself.

SOUTH RANGE DEPOSITS

The Murray Mine (Figure 1) has been described by Souch, Podolovsky *et al.* (1969) and is a relatively simple example of this group. Huronian "greenstones" and the 2.2 Ga old Murray Pluton form the Footwall to the deposit. Massive sulphide minerals containing inclusions of Footwall material and of the suite of peridotites, pyroxenites, and gabbros described in the previous chapter (Grant and Bite, Chapter 12, this

NORTH RANGE DEPOSITS

The Strathcona Mine is typical of the North Range deposits. It has been described by Naldrett and Kullerud (1967), Cowan (1968), and Abel *et al.* (1979). As seen in Figure 2, the ore is associated with an inclusion-bearing phase of the Sublayer. A sharp contact exists between this, the "xenolithic norite", which carries 1 to 5 modal % sulphide, and the relatively unmineralized Main Mass of felsic norite. The proportion of sulphide in the xenolithic norite increases downward to as

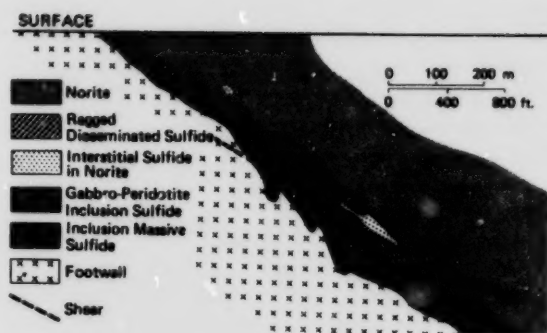


Figure 1. Generalized sections through the Murray Mine looking west (after Souch, Podolsky *et al.* 1969).

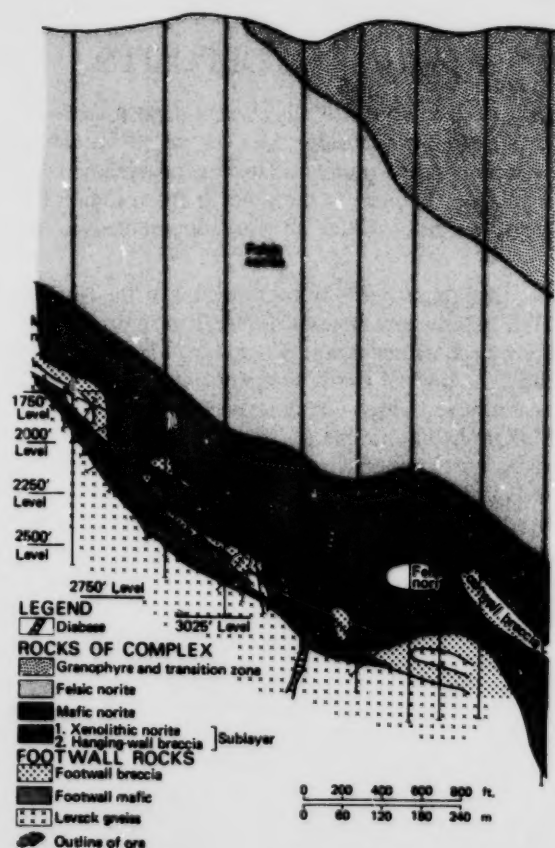


Figure 2. Vertical cross-section (21,200 E) through the Strathcona Mine, looking east (after Naldrett and Kullerud 1967).

much as 60% near the base where it constitutes ore. The inclusions consist predominantly of mafic and ultramafic cumulates, although felsic and fine-grained mafic rocks are also present.

The Footwall is characterized by the Footwall Breccia, a heterogeneous rock composed of inclusions of felsic gneiss, amphibolite similar to that found in the

felsic gneiss, mafic and ultramafic cumulates, and, very rarely, fragments of Main Mass mafic norite. These inclusions are set in a matrix of fine-grained equant plagioclase, quartz grains, and wispy amphibole, commonly cemented together by large, interstitial grains of "flood" quartz. In places, the Sublayer is gradational into the matrix of the Footwall Breccia with an increase in plagioclase and quartz content, and a change in the shape of the plagioclase grains. Elsewhere, the contact is sharp, in places Footwall Breccia protrudes up into the Sublayer. The Footwall Breccia matrix may be seen to be in sharp contact with the underlying Levack Gneiss, with thin stringers penetrating and encircling, or partly encircling, masses of gneiss. The gneiss itself is cut by veins, stringers, and irregular masses of Sudbury Breccia in places.

Much of the ore at the Strathcona Mine occurs as a dissemination in the Footwall Breccia matrix, as massive or semi-massive stringers cutting the matrix, and, rarely, as massive fragments within the matrix. Farther into the Footwall, massive stringers of ore following fractures in the gneiss, constitute the "Deep Zone" at the Strathcona Mine. This ore can be as much as 100 m from the basal contact of the Complex. Massive stringers of very Cu-rich ore (the Cu-Zone) occur even farther into the Footwall, and extend more than 300 m from the Sublayer contact.

The Strathcona deposit is marked by a systematic increase in Cu, Ni, Cu/(Cu + Ni) ratio, Pt, Pd, and Au and a decrease in Co, Ru, Ir, and Os away from the Sublayer and into the Footwall.

Important features typical of all North Range deposits are the presence of a Sublayer that is very distinct from the Main Mass of the Complex, the presence of Footwall Breccia (this is a feature not seen on the South Range), and the presence of strong zoning in metal ratios which parallels the lower contact of the Complex.

OFFSET DEPOSITS

The Copper Cliff North and South deposits, described by Souch, Podolsky *et al.* (1969) and by Grant and Bite (Chapter 12, this volume), are typical of the offset environment. Because a description already exists in this volume, space will not be given to them in this section (see Cochrane, Chapter 14, this volume).

The Frood-Stobie deposit (Zurbrigg *et al.* 1957; Hawley 1965; Souch, Podolsky *et al.* 1969) is atypical of the offset environment; because of its economic importance, and because it appears to constitute a link with other types of deposits, it will be described briefly here.

In plan view, the Frood-Stobie deposit resembles a dike, emplaced within a zone of Sudbury Breccia parallel to the southern margin of the Complex. In

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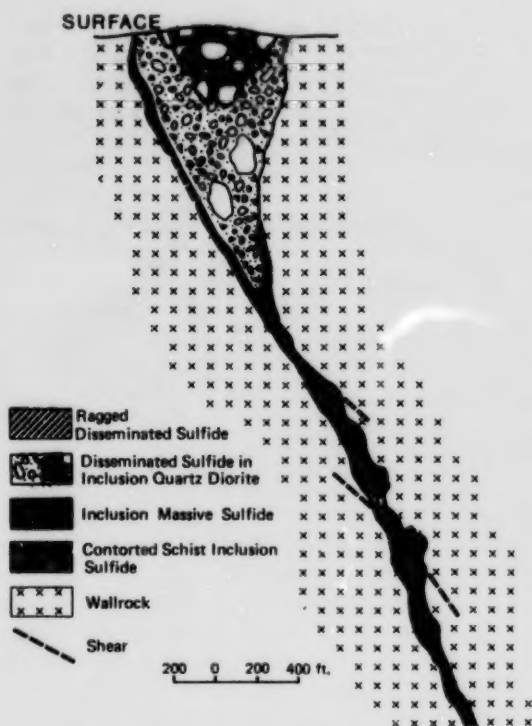


Figure 3. Generalized section through the Frood orebody, looking southwest (after Souch, Podolsky *et al.* 1969).

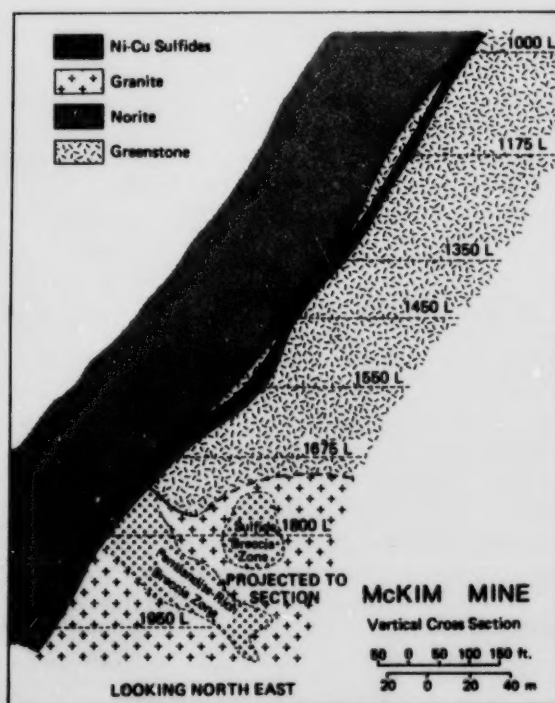


Figure 4. Cross-section showing the dip of the main ore zone and position of the pentlandite-rich and Footwall Breccia ore at McKim Mine. Looking east (after Clarke and Potapoff 1959).

cross-section (Figure 3), the deposit is wedge-shaped, tapers downward and dips steeply toward the Main Mass of the Complex. Massive, inclusion-bearing sulphide is concentrated along the edges and toward the base of the wedge, while the upper part of the orebody consists of disseminated sulphide in inclusion-bearing quartz diorite. A pronounced vertical zoning is present with Cu and the Cu/(Cu + Ni) ratio increasing downward into a chalcopyrite and cubanite-rich ore in the lower levels of the mine. An unusual aspect of the deposit is the siliceous mineral zone which occurs at its base. This zone is anomalously rich in platinum group elements (PGE's), and may have formed as a result of hydrothermal activity. It is perhaps curious that similar zones have not been observed to be associated with the Cu-rich parts of other deposits, for example with the Cu-Zone at the Strathcona Mine.

FAULT-RELATED DEPOSITS

The prime examples of this class of deposit are those of the East, Falconbridge, and Garson Mines which form part of this volume and to which the reader is referred (*see* Chapters 14 through 17, this volume). For the most part, these are not documented in the literature.

One deposit that is documented, is the McKim Mine (Clarke and Potapoff 1959). Part of this deposit is enclosed within granite (Figure 4). Where this is the case, the normal pyrrhotite-pentlandite-chalcopyrite assemblage, which characterizes those parts of the McKim Mine that have a "greenstone" Footwall, gives way to one consisting dominantly of pentlandite and pyrite within a gangue of quartz and carbonate. Pyrrhotite is much less common than in most deposits and chalcopyrite is almost non-existent. The pentlandite is much coarser than normal and is extensively replaced by pyrite.

Clarke and Potapoff (1959) considered that the ore represented a zone of normal pyrrhotite-rich Sudbury ore that became engulfed in a granite younger than the Sudbury Igneous Complex granite. On surface in the vicinity of the mine, veins of granite can be observed to cut back into the Complex from the Murray Pluton forming the Footwall. These veins are thought to be due to the remobilization of older granite by the heat of the Complex. Curiously, this remobilization has been on a sufficient scale to effect a major reworking of the mineralogical and chemical composition of the deposit.

GENESIS

The concept of a magmatic origin for the Sudbury ores is pervasive throughout much of this chapter. This concept is widely, but not universally accepted.

Wandke and Hoffman (1924) concluded as a result of a petrographic study of the ores that they were emplaced hydrothermally. Fleet (1977) noted that the composition of individual sulphide blebs in "buck-shot" ore varied widely, interpreted this as being inconsistent with their emplacement as droplets of molten sulphide, and argued also for a hydrothermal origin. Fleet *et al.* (1977) and Fleet and MacRae (1983) have studied the partitioning of Ni and Fe between olivine and molten sulphide experimentally, and have obtained exchange partition coefficients which are incompatible with the observed partitioning of these elements between naturally co-existing olivine and sulphide. These authors, therefore, cast doubt upon a magmatic origin for most Ni-Cu deposits, including Sudbury.

On the other hand, Rajamani and Naldrett (1978) obtained exchange partition coefficients for Ni and Fe, and Nerst distribution coefficients for Cu and Co between molten sulphide and basaltic magmas. These coefficients are compatible with a magmatic origin and are in direct disagreement with the results of Fleet and his co-workers. The work of Bector (1981, 1982) and Bector and Yoder (1983) indicated a possible answer to this conundrum. Bector has shown that both sulphide-olivine and sulphide-silicate magma partitioning are strongly dependent on the prevailing oxygen fugacity. At low oxygen fugacities, Bector obtained values in line with Fleet and MacRae (1983), but under more oxidizing conditions, similar to those believed to prevail in nature, Bector obtained values similar to those of Rajamani and Naldrett (1978). Neither Fleet and MacRae nor Rajamani and Naldrett controlled oxygen fugacity in their experiments, although the latter used bulk compositions which they believed generated values of fO_2 close to those on the Ni-NiO buffer that are thought to apply in nature.

It is not appropriate in this special volume to give a detailed defence of the magmatic origin of Ni-Cu ores in general. The reader is referred to Naldrett (1979) for some of this author's views on the subject. It will suffice to say that

1. the basal nature of the concentration of most of the ore zones
2. the concentration of Co and the Platinum Group Elements in the ores in addition to Ni and Cu
3. the absence of significant amounts of Zn and Pb (common constituents in hydrothermally deposited ores but ones which would be expected to be excluded from magmatic sulphides on the basis of their low partition coefficients)
4. the lack of major hydrothermal alteration
5. the presence of textures highly suggestive of the co-existence of a magmatic sulphide liquid and partially crystalline silicate magma

are amongst the features that have persuaded many geologists that the ores are indeed magmatic in origin.

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CHAPTER 13

Mineralogy and Composition of the Sudbury Ores

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ABSTRACT

The minerals pyrrhotite, pentlandite, chalcopyrite, and pyrite account for the vast bulk of the sulphides in the Sudbury ores. At temperatures $> 250^{\circ}\text{C}$, all of the pentlandite would have been in solid solution in pyrrhotite as monosulphide solid solution (Mss). At temperatures just below the solidus, much of the chalcopyrite would also have been in solid solution in cupriferous Mss, so that the sulphide magma responsible for the ores would have crystallized as Mss and magnetite. The liquidus and solidus temperatures of the melts giving rise to most of the ores would have been of the order of 1120° and 1040°C , respectively.

Fractional crystallization of Mss from a sulphide melt over this temperature interval would have given

rise to a cumulate enriched in Fe, Co, Rh, Ru, Ir, and Os, and a fractionated liquid enriched in Ni, Cu, Pt, Pd, and Au. Fractionation of this kind is thought responsible for the compositional zoning exhibited by many deposits, in which the Ni, Cu, Pt, Pd, and Au are enriched toward the Footwall, and for the formation of Cu-rich stringers which occur several hundred m into the Footwall at the Strathcona Mine.

On the other hand, compositional variation between deposits is marked by very pronounced differences in the tenor of all of the PGE as a group, and to a lesser extent of Ni and Cu. These differences are best explained as the result of the segregation of varying amounts of sulphide from a given batch of magma. Those deposits that formed from sulphide liquid that has segregated in large proportion, or at a late stage

TABLE 13.1: MINERALS OF THE SUDBURY ORES.

METALLIC MINERALS NAME	FORMULA	NOTES	REFERENCES
MAJOR			
Pyrrhotite			
Hexagonal	$\text{Fe}_{(1-x)}\text{S}$	Distribution of hexagonal and monoclinic studied intensively at Strathcona Mine	Cowan (1968) Corlett (1972)
Monoclinic	$\text{Fe}_{(1-x)}\text{S}$		
Pentlandite	$(\text{Fe,Ni})_9\text{S}_8$	Ni content 33 to 35 wt. % Co content 1 wt. %	Hawley and Stanton (1962)
Chalcopyrite	$(\text{CuFe})\text{S}_2$		Hawley and Stanton (1962)
Magnetite	Fe_3O_4	Magnetite in the ores is low in TiO_2	Hawley and Stanton (1962) Naldrett and Kullerud (1967)
Pyrite	FeS_2	4 types 1. Pink Nickelian 2. Early Resorbed 3. Exsolved 4. Hypogene Replacement	
MINOR			
Cubanite	CuFeS_2	Found particularly in the Frood-Stobie deposit and in Cu-zone at Strathcona.	Hawley and Stanton (1962) Abel <i>et al.</i> (1979)
Galena	PbS	Found as small veins in fractures and as small flecks in pyrite.	
Sphalerite	ZnS	Present with chalcopyrite as late veins and fault filling.	Hawley and Stanton (1962)
Millerite	ZnS	Originally regarded as secondary. Hypogene mineral found in Footwall at Strathcona Mine.	
Niccoline	NiAs	Found at Worthington, Frood, and Garson in association with other arsenides	Hawley and Stanton (1962)
Gersdorffite	NiAsS	Occurs with chalcopyrite and as late stage veins	Hawley and Stanton (1962) Cabri and Laflamme (1976)
Cobaltite	CoAsS		
RARE			

TABLE 13.1: MINERALS OF THE SUDBURY ORES. CONTINUED.

METALLIC MINERALS NAME	FORMULA	NOTES	REFERENCES
Gold	Au	Found in siliceous mineral zone at Frood Mine	Hawley and Stanton (1962) Michener (1940)
Silver	Ag	Found near base of Frood Mine	Hawley and Stanton (1962)
Bismuth	Bi	Found associated with galena or with parkerite and bornite at Frood	Hawley and Stanton (1962)
Tetradymite	$\text{Bi}_2\text{Te}_3\text{S}$	Commonly associated with veins of galena	Hawley and Stanton (1962)
Hessite	Ag_2Te	Found at Frood Mine	Hawley and Stanton (1962)
Maucherite	$\text{Ni}_{11}\text{As}_8$	Commonly occurs with niccolite and gersdorffite	Hawley and Stanton (1962)
Bornite	Cu_5FeS_2	Only observed in Cu-rich zones at Frood deposit	Hawley and Stanton (1962)
Parkerite	$\text{Ni}_3\text{Bi}_2\text{S}$		Michener (1940)
Schapbachite	AgBiS_2	Frood Mine—1 grain observed	Hawley and Stanton (1962)
Altaite	PbTe	Found at Coleman, Frood, and Crean Hill Mines, often associated with PGM	Cabri and Laflamme (1974 and 1976)
Argentiferous Pentlandite	$(\text{FeNi})_8\text{AgS}_8$	Light pink, probably confused with bornite	Karpeakov <i>et al.</i> (1973)† Cabri and Laflamme (1976)
Breithauptite	$\text{Ni}_3(\text{Bi,Sb,Te})_2\text{S}_8$		
Hauecorinite			
Mackinawite			
Wehrlite	$(\text{BiPb})(1.05-1.28)$ $(\text{TeSb})(0.95-0.72)$	Associated with chalcopyrite-cubanite	Cabri and Laflamme (1976)
PGM (in relative order of abundance)			
Michenerite	PdBiTe	Principal Pd mineral at Sudbury and occurs in most deposits	Cabri and Laflamme (1976) Hawley and Berry (1958)
Moncheite	PtTe_2	Observed at Creighton and Levack West	Cabri and Laflamme (1976)
Sperrylite	PtAs_2	Most common Pt mineral of South Range	Hawley and Stanton (1967) Cabri and Laflamme (1976)
Insizwaite	PtBi_2	Found at Coleman Mine	
Sudburite	PdSb	Found at Copper Cliff South and Frood	Cabri and Laflamme (1976)
Froodite	PdBi_2	Found at Frood, Vermilion, Creighton, Levack West, and Coleman	Hawley and Berry (1958) Cabri and Laflamme (1976)
Kotulskite	PdTe	Found at Levack West and Creighton	Cabri and Laflamme (1976)
Niggliite	PtSn	Found at Coleman Mine	Cabri and Harris (1972)
Merenskeyite	PdTe_2	Found at Creighton, Crean Hill, and Levack West	Cabri and Laflamme (1976)
Mertieite II	$\text{Pd}_3(\text{SbAs})_3$	Found at Creighton Mine	Cabri and Laflamme (1976)
Unnamed	$\text{Ps}(\text{Bi,Sb,Te})$	Found at Vermilion Mine	Cabri (1973) Cabri and Laflamme (1976)
Unnamed	$\text{Ag}_4\text{Pd}_3\text{Te}_8$	Found at Levack Mine West	Cabri and Laflamme (1976)
Palladian melonite	$(\text{Ni,Pd})(\text{Te,Bi})_2$	Found at Falconbridge, Strathcona, Crean Hill, and Creighton	Cabri and Laflamme (1976)
SECONDARY			
Violarite	FeNi_2S_4	Found in many ores subject to weathering	Hawley and Stanton (1962)
Marcasite	FeS_2	Found as a replacement in cross-cutting seams and fractures	Hawley and Stanton (1962)
Valleriite	$(\text{Fe,Cu})\text{S}_2$ $(\text{Mg,Al})(\text{OH})_2$	Found in chalcopyrite-rich samples	Hawley and Stanton (1962)

†Not available in AGI Bibliographies

from a particular batch of magma contain lower concentrations of the PGE and Ni and Cu, than those that had segregated in lesser proportion, or at an early stage in the segregation process.

MINERALOGY

Early mineralogical work at Sudbury has been summarized by Hawley and Stanton (1962) who contributed many of their own observations. These authors reported 32 metallic minerals as confirmed species. Subsequent mineralogical studies have involved investigations of the nature of the pyrrhotite (Cowan 1968), use of the microprobe in determining the ranges in composition of the major minerals, and studies of the platinum group minerals (PGM); (Cabri and Laflamme 1976; Cabri and Laflamme in press).

Metallic minerals identified in the ores are summarized in Table 13.1. Details of their composition and occurrence are best obtained from key references that are cited in the table; space does not permit us to reproduce the data. Here, only some of the major groupings of minerals will be discussed, and relevant phase equilibria studies will be cited where appropriate.

Fe-Ni-S Minerals

These include pyrrhotite, pentlandite, and pyrite. Pyrrhotite is the principal host for all other sulphide min-

erals. Two distinct forms have been identified, ferromagnetic monoclinic pyrrhotite and diamagnetic hexagonal pyrrhotite. The distribution of the 2 forms throughout the Strathcona Mine has been discussed by Cowan (1968). Where the monoclinic variety is the less common of the 2, it may occur (Naldrett and Kullerød 1967):

1. rimming grains of hexagonal pyrrhotite
2. spreading out away from fractures (Photo 13.1)
3. in association with pentlandite (Photo 13.2), often forming sheaths around exsolved pentlandite lamellae

Where the monoclinic variety is the more common, textures in many samples suggest that it has developed through growth of the features just described.

Pentlandite occurs as large (1 to 3 cm diameter) irregular masses, as smaller (< 1 cm diameter) masses at triple junctions between pyrrhotite grains, as thin (< 3 mm) rims around pyrrhotite grains (Photo 13.3), and as very fine (1 to 4 microns thick, 10 to 100 microns long) lamellae oriented parallel to the 0001 parting of pyrrhotite (Photo 13.4). Pyrite occurs as irregular, somewhat resorbed grains and as small (1 mm diameter) euhedral grains around the margins of pyrrhotite grains (Photo 13.5).

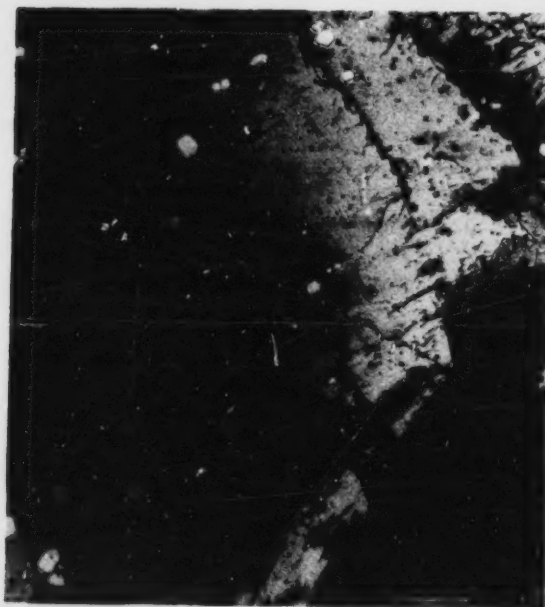


Photo 13.1. Intergrowth of hexagonal pyrrhotite (light grey) and monoclinic pyrrhotite (very dark grey to black). Small, equant, white masses are pyrite. Note how the development of monoclinic pyrrhotite is related to fractures cross-cutting the ore. Section stained with ammonium dichromate + HCl. Reflected light. 100X.

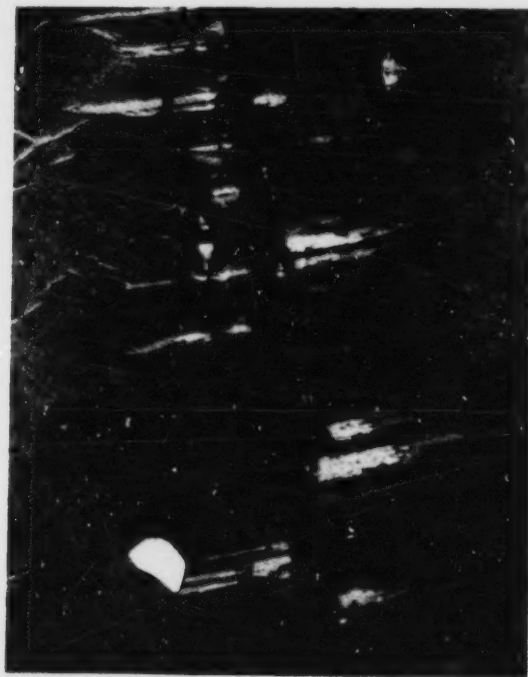


Photo 13.2. Fracture (black) cutting section composed largely of hexagonal pyrrhotite (medium grey). Small flames of exsolved pentlandite (white) are developing on either side of the fracture. These are partially sheathed by, and terminate in lamellae of monoclinic pyrrhotite (light grey). Note the equant mass of pyrite (white) within the hexagonal pyrrhotite. Section stained with ammonium dichromate + HCl. Reflected light. 200X.

Naldrett and Kullerud (1967) discussed the crystallization of Fe-Ni sulphide ores of the bulk composition of those found at Sudbury in the light of phase relations in the Fe-Ni-S system. These authors pointed out that the $\text{Fe}_{(1-x)}\text{S}-\text{Ni}_{(1-x)}\text{S}$ monosulphide solid solution (Mss) is continuous across the system from solidus temperatures to below 300°C. The bulk composition of Sudbury ore plots within and toward the sulphur-rich side of the Mss (Figure 13.1) as it occurs at 600°C. With cooling, the range in metal:sulphur ratios covered by the Mss narrows (Naldrett *et al.* 1967) and ore compositions of the Sudbury-type will exsolve some pyrite. Pentlandite will not form until the Mss breaks down and tie-lines joining the Ni-rich and Ni-poor variants resulting from the breakdown are replaced by those joining pyrite and pentlandite. Craig (1973) showed that this will happen between 200° and 250°C (Figure 13.2). Thus, the formation of the second-most common mineral in the Sudbury ores, the mineral whose existence enables a reasonable Ni concentrate to be extracted from them and thus accounts for their economic viability, is a very low temperature phenomenon.

Not all Ni exsolves as pentlandite; some remains in solid solution in pyrrhotite. Corlett (1972) reported values of 0.1 to 1.2 wt% Ni in pyrrhotite. Furthermore, some pentlandite occurs as the fine flames discussed above. These are too fine to be separated by



Photo 13.3. Pentlandite (light grey, blocky texture) that has exsolved to form rims around grains of pyrrhotite (medium grey). Reflected light. 4X.



Photo 13.4. Fine, flame-like lamellae of exsolved pentlandite (white), extending out from grains of silicate (black) around magnetite (dark grey), into pyrrhotite (light grey). Reflected light. 750X.

flotation, and hence are lost with the pyrrhotite tailings. Consequently, the low temperature cooling history of a Sudbury ore is most important with respect to the growth of coarse grains of pentlandite and hence to its milling characteristics.

Cu-Fe-S Minerals

These include chalcopyrite, cubanite, and rare amounts of bornite. Chalcopyrite is ubiquitous and accounts for by far the major part of the Cu in the Sudbury area. Cubanite occurs in many deposits associated with chalcopyrite, but is particularly concentrated in the deeper parts of the Frood-Stobie deposit and in the Cu-Zone, deep in the Footwall at the Strathcona deposit, where it comprises 18% of the total sulphide (Abel *et al.* 1979). Where cubanite is present in minor amounts, it occurs as exsolution blades in chalcopyrite; where it makes up a greater proportion of the ore as at the Frood or Strathcona Mines, it is present in irregular masses, commonly enclosing pyrrhotite, in addition to the exsolution blades.

As seen in Figure 13.3, the Cu-Fe-S system is dominated by large areas of solid solution at temperatures just below the solidus. On cooling, these areas break down and, at Cu:Fe ratios of < 1, pyrite, pyrrhotite, and chalcopyrite are the usual products. Where

the sulphide content is low, as often seems to be the case in fractionated, Cu-rich residual liquids, pyrite is absent and pyrrhotite, chalcopyrite, and cubanite form the stable assemblage.

Abel *et al.* described the exsolution of pentlandite lamellae along the edges of cubanite blades in chalcopyrite; this indicated that Ni dissolved in the Cu-rich solid solution that broke down to form the Cu minerals, so that phase relations in the Cu-Fe-S system provided only a rough guide to what may have happened in the more complex natural system of the ores.

Bornite occurs in only the most Cu-rich parts of ore deposits. Cabri and Laflamme (1976) believed that argentiferous pentlandite had been misidentified as bornite by many of the early investigators.

Some Other Minerals

Magnetite is a very common mineral, usually present in amounts ranging from 5 to 10 modal %, although some areas of some deposits have up to 25 %, and zones of nearly massive magnetite have been reported. Sphalerite and galena occur in very minor amounts, particularly in Cu-rich zones of the main ores and as late, cross-cutting veins. The arsenides, niccolite and

maucherite, and sulfarsenides, gersdorffite and cobaltite, commonly occur together, but are largely restricted to the South Range ores (Hawley and Stanton 1962; Cabri and Laflamme 1976). This is consistent with the observation reported below that the As contents of the South Range deposits are a factor of 20 or more greater than those of the North Range. Compositional ranges for cobaltite and gersdorffite overlap, with Co ranging between the 2 minerals from 5 to 21 wt %, and Ni from 9 to 25 wt %.

Platinum Group Minerals (PGM)

Cabri and Laflamme (1976) have identified or confirmed 13 PGM in the Sudbury ores. These are listed in Table 13.1 in the approximate order of their abundance. Cabri and Laflamme remarked that the South Range and Offset deposits were characterized by the presence of As-bearing minerals and the absence of Sn-bearing minerals, while Sn-bearing minerals were present and As-bearing minerals were rare in deposits on the North Range. These authors also detected significant amounts of platinum group elements (PGE) in solid solution in the As-bearing minerals. Cobaltite contains from 1200 to 7600 ppm Pd, from < 400 to 1900 ppm Pt, and from < 500 to 15 000 ppm Rh; gersdorffite contains from 500 to 2000 ppm Pd, from < 400 to 2500 ppm Pt, and from < 500 to 30 000 ppm Rh; niccolite contains < 400 ppm of each of Pd, Pt, and Rh; and maucherite contains from < 800 to 1000 ppm Pd, and < 500 ppm of both Pt and Rh.

Cabri and Laflamme (in press) have found that 91 % of the Pt in 1 bulk concentrate could be accounted



Photo 13.5. Small euhedra of pyrite partly encircling a pyrrhotite grain (centre of picture). Pentlandite (medium grey) can just be discerned as rims at margins of pyrrhotite grains. Reflected light. 40X.

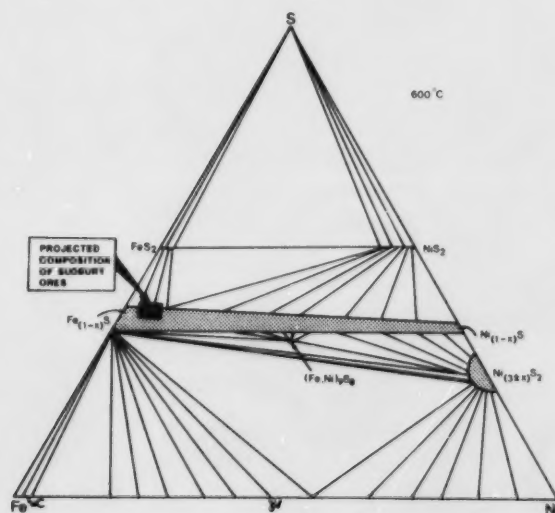


Figure 13.1. Phase relations in a part of the Fe-Ni-S system at 600°C. The composition of sulphides in Sudbury deposits plot within or very close to the field of the Monosulphides ($\text{Fe}_{(1-x)}\text{S}$ - $\text{Ni}_{(1-x)}\text{S}$) solid solution (MSS) within the shaded area.

for by sperrylite, by solid solution in the sulfarsenides, by moncheite and by platinumian michenerite; in contrast, only 41% of the Pd could be accounted for by michenerite, and by solid solution in arsenides or sulfarsenides, merenskyite, and palladian moncheite. It is generally believed that significant amounts of Pd can substitute in pentlandite (Cabri and Laflamme 1974, reported 1.4 wt% Pd; Todd *et al.* 1982, reported 3.5 wt% Pd in pentlandite from the PGE zone in the Stillwater Complex). Nevertheless, Cabri *et al.* (1983) were unable to detect even 1.8 ppm Pd in Sudbury pentlandite with a proton microprobe. Clearly, more work is required before the provenance of the PGE at Sudbury can be taken as completely solved.

CHEMICAL COMPOSITION OF THE ORES

Early work on the composition of the Sudbury ores was summarized by Hawley (1962). This was followed by Hawley's (1965) discussion of zoning at the Frood-

Stobie deposit, and Naldrett and Kullerud's (1967) and Cowan's (1968) discussions of zoning at the Strathcona Mine. Keays and Crocket (1970) and Chyi and Crocket (1976) studied the distribution of PGE in mineral separates at the Strathcona Mine. Following the development of a method for analyzing PGE in bulk ores (Hoffman *et al.* 1978), Hoffman *et al.* (1979) reported on the PGE content of 3 Sudbury deposits. Naldrett (1981) compared the trends of major and trace element variation within the Sudbury ores with those of other Ni-Cu deposits, and Naldrett *et al.* (1982) documented and suggested explanations for major elements and PGE variation within and between 5 Sudbury deposits.

The composition of the sulphide component (ignoring silicates and magnetite) of these 5 deposits is given Table 13.2. These have been calculated from the analytical data according to the method outlined by Naldrett (1981).

Major Elements

If the silicate components are ignored, and those elements that are thought to have been constituents of the sulphide magmas responsible for the ores are focussed on, the major components are Fe, S, Ni, Cu, and O, in decreasing order of abundance.

Fe, S, and O

Considering Fe, S, and O alone, Naldrett (1969) noted that the composition of most magmatic sulphides falls in the pyrrhotite field of the Fe-S-O system. Naldrett, and subsequently, Shima and Naldrett (1975), pointed out that the proportion of Fe, S, and O in a sulphide liquid segregating as dispersed droplets from a mafic silicate magma will be controlled by the fugacities of O_2 and S_2 (fO_2 and fS_2) prevailing in the magma (Figure 13.4). Because these fugacities are buffered within certain limits by the composition of the host magma (particularly by its total Fe concentration, its $Fe^{3+}/$

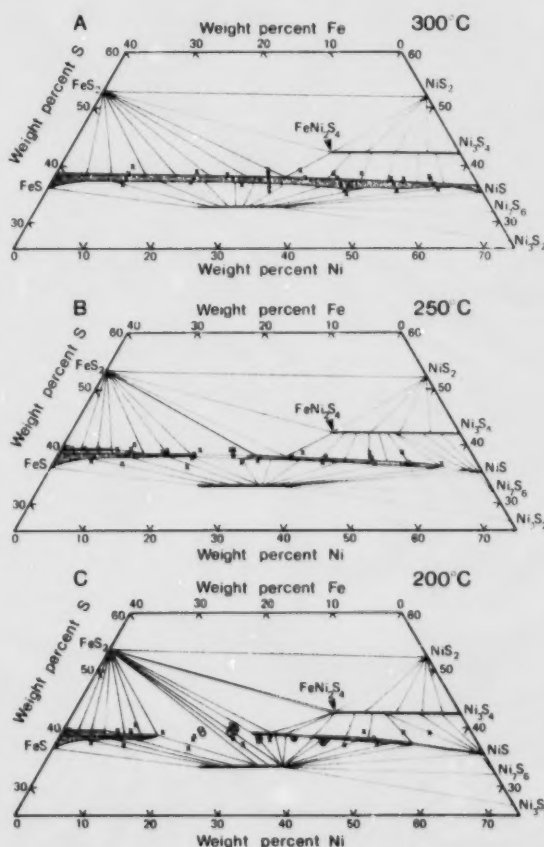


Figure 13.2. Phase relations in the central part of the Fe-Ni-S system at (A) 300°C, (B) 250°C, (C) 200°C. Selected experimental compositions are designated x. Open circles are compositions in which pyrite-pentlandite assemblages were formed (after Craig 1973).

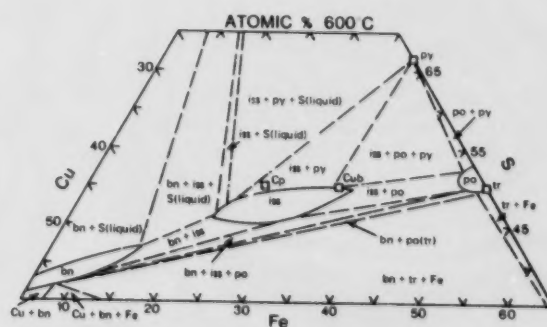


Figure 13.3. Phase relations in the central part of the Cu-Fe-S system at 600°C.

CHAPTER 13

TABLE 13.2: METAL CONTENT OF SUDBURY ORES RECALCULATED TO 100% SULPHIDE.

	Ni	Wt.% Cu	Co	Pt	Pd	Rh	ppb Ru	Ir	Os	Au	Zn	ppm ¹ Pb	As	S/Se	$\delta^{34}\text{S}$	Cu Cu + Ni	Pt + Pd (Ru + Ir + Os)
LEVACK WEST																	
Footwall Breccia Ore	5.6	3.3	0.17	1098	1223	228	73	62	26	166	153	28	—	4900	2.6	0.37	14.4
Footwall Ore	5.8	5.3	0.11	1334	1350	53	22	17	10	97	529	39	—	4050	2.9	0.48	54.8
Cu-rich Stringers	2.6	27.8	0.027	3370	5948	10	<3	0.3	<2	167	3716	258	—	1860	3.13	0.91	1760
Average ²	5.7	3.7	—	1150	1250	186	60	47	22	150	227	31	<3.5	4550	2.71	0.39	18.6
STRATHCONA																	
Hanging Wall Ore	3.1	0.37	0.21	114	105	60	52	29	20	19	122	9	—	—	—	0.11	2.2
Footwall Breccia Ore	3.4	1.2	0.14	413	380	20	12	7	4	78	160	21	—	—	—	0.26	34.5
Footwall Ore	4.0	2.3	0.13	750	701	16	4	4	3	112	227	26	—	—	—	0.37	132
Cu Zone	0.51	32.3	0.087	137	40	4	3	0.2	2	13	2750	—	—	—	—	0.98	34
Average (i) ³	3.63	1.23	0.15	420	372	30	21	12	8	54	233	26	—	—	—	0.25	19.3
Average (ii)	3.63	2.8	0.14	590	511	19	9	8	5	79	—	—	—	—	—	0.44	50
LITTLE STOBIE NUMBER 1																	
Average	3.8	4.4	0.19	1930	2120	119	123	62	29	862	100	15	160	3800	1.08	0.54	18.9
LITTLE STOBIE NUMBER 2																	
Average	4.0	3.6	0.17	2130	3170	303	247	113	46	868	96	14	93	3600	0.46	0.47	13
FALCONBRIDGE																	
Average	5.35	1.52	0.22	546	381	287	225	144	40	174	120	14	—	—	—	0.22	2.3

¹ Zn, Pb, and As have not been recalculated to 100% sulphide.

² Does not include Cu-rich stringers.

³ Average (i) is straight average of data, Average (ii) is a weighted average to give the Cu/(Cu + Ni) ratio of the ore reserves.

Fe²⁺ ratio, and its SiO₂ concentration); and because all mafic magmas in the crustal environment tend to have rather similar values of these intensive parameters, magmatic sulphides tend to have rather similar proportions of these elements. For example, one would not expect to see under normal circumstances an ore composed of 60% primary magnetite.

Naldrett (1969) also made the point that as a sulphide melt crystallizes pyrrhotite, oxygen will become concentrated in the diminishing mass of melt, with the result that the $f\text{O}_2$ of the melt will rise. If this sulphide melt is still distributed as droplets within its silicate host magma, this oxygen may diffuse out of the droplets into the host with its lower $f\text{O}_2$. The tendency to lose oxygen in this way will be lessened if the droplets have settled and coalesced to form a pool of sulphide. The tendency will always remain, however, and the proportion of magnetite within an ore deposit may always represent less oxygen than was dissolved in the original sulphide magma. An estimate of the composition of the Strathcona ore is given by point B in Figure 13.4. This corresponds to an $f\text{O}_2$ of $10^{-10.5}$ atm, which is

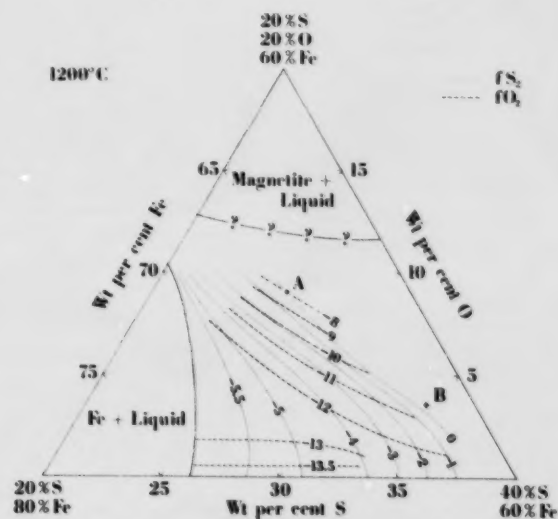


Figure 13.4. Variation in $\log f\text{S}_2$ and $\log f\text{O}_2$ with composition of Fe-S-O liquid at 1200°C. The isobars are constructed from data given by Rosenqvist (1954), Bog and Rosenqvist (1958), and Nagamori and Kameda (1965). (after Naldrett 1969).

TABLE 13.3: AVERAGE COMPOSITION OF SULPHIDE LIQUIDS RESPONSIBLE FOR CERTAIN ORES.

MINE	Wt. %			ppb						
	Ni	Cu	Co	Pt	Pd	Rh	Ru	Ir	Os	Au
Strathcona	3.6 (3.6)	1.2(2.8) (2.4)	0.15(0.14) (0.14)	420(590)	372(511) (410)	3.0(19)	21(9)	12(8)	8(5)	54(79)
Levack West	5.7 (5.5)	3.7 (3.6)	0.16 (0.17)	1154	1253 (1350)	186	60	47	22	150
Little Stobie Number 1	3.8 (3.6)	4.4 (4.0)	0.19 (0.17)	1930	2120 (2020)	119	123	61	29	862
Little Stobie Number 2	4.0 (4.0)	3.6 (4.4)	0.17 (0.17)	2130	3170 (3090)	303	247	113	46	860

Figures in parentheses are compositions modeled as discussed in the text

somewhat lower than that estimated for most mafic magmas at 1200°C, indicating that the ore may have lost some oxygen.

Ni and Cu

Most Ni is now present in the ores as pentlandite, although up to 1 wt% remains in solid solution in pyrrhotite. Copper is present largely as chalcopyrite. As emphasized previously, all of the Ni and most of the Cu would be dissolved in a monosulphide solid solution at elevated temperatures (250°C in the case of Ni, 700°C in the case of Cu), so that initially the ore would have crystallized as magnetite plus monosulphide solid solution.

Bulk Ni content varies from a low of 3.63 wt% at the Strathcona Mine to a high of 5.73 at the Levack West Mine, while Cu ranges from a low of 1.23 wt% at the Strathcona Mine (more correctly about 2.8 if the Cu zone present in the Footwall is included), to a high of 4.4 at the Little Stobie Number 1 Mine. The Cu/(Cu + Ni) ratios range from a low of 0.22 at the Falconbridge Mine to a high of 0.54 at the Little Stobie Number 1 Mine.

Some of the deposits for which data are given in Table 13.2 have a pronounced internal zoning. Figure 13.5 illustrates the increase in the Ni content of sulphide away from the hanging wall and through the Footwall Breccia at the Strathcona Mine. The zoning is brought out further in Table 13.3 from which it is seen that while the average Ni content in 100% sulphide rises from 3.1 wt% in the hangingwall ore to 4.0% in the Footwall ore, and then drops to 0.51 in the Cu zone, the average Cu content rises from 0.37 to 2.3 to 32.3 wt% and the Cu/(Cu + Ni) ratio rises from 0.11 to 0.37 to 0.98. Similarly, at the Levack West Mine, while average Ni rises from 5.6 in the Footwall Breccia ore to 5.8 in the Footwall ore, and then drops to 2.6 in the Cu-rich stringers in the Footwall adjacent to the Footwall ore, Cu rises from 3.3 to 5.3 to 27.8 wt%, and the Cu/(Cu + Ni) rises from 0.37 to 0.48 to 0.91.

Naldrett (1981) has discussed the relationship between the Ni and Cu contents of ore deposits at Sudbury and elsewhere. He has concluded that, using partition coefficients for the partitioning of Ni and Cu between coexisting sulphide and mafic silicate melts of 275 and 250 respectively, as determined by Rajamani and Naldrett (1978), the ranges of Ni and Cu presented above are those to be expected for equilibration with a mafic magma with the composition of that believed to be responsible for the Sudbury Igneous Complex. A possible scenario for the development of the ranges in composition observed, and an explanation for the intra-deposit zoning follows in a later section.

Trace Elements

Co

Pentlandite is the host for the bulk of the cobalt in the Sudbury ores (Naldrett 1961), small amounts remain in solid solution in pyrrhotite, and a minor amount is present in pyrite. Gersdorffite and cobaltite, which can contain up to 25 wt% Co, account for only a small proportion of the total.

Cobalt content varies from a low of 0.15 wt% at the Strathcona Mine to a high of 0.22 at the Falconbridge Mine. It is markedly zoned across deposits for which there are data, showing inverse behaviour to Cu (see Table 13.2).

Zn and Pb

Zinc is present as sphalerite, which is usually found in close proximity to chalcopyrite. Both North Range deposits average about 230 ppm Zn, while those on the South Range average about 100 ppm. Naldrett (1981) pointed out that the concentration of Zn in sulphide ores was similar to that in unmineralized examples of their host rocks, which is consistent with the experimental findings of Shimazaki and MacLean (1976), that the sulphide melt/silicate melt partition coefficient is about one. For this reason, no attempt has been

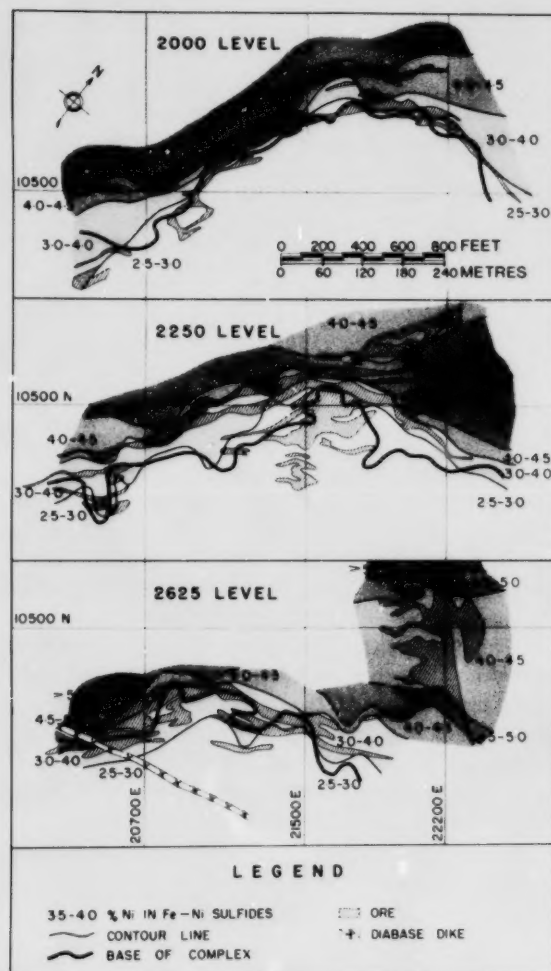


Figure 13.5. Zoning in the concentration of Ni in iron-nickel sulphides on 3 horizontal levels (given as feet below the surface) in the Strathcona Mine (data after Cowan 1968). (after Naldrett and Kullerud 1967).

made to recalculate the Zn data to concentration in 100% sulphide. Zinc is much more concentrated in the Cu-rich zones of ore deposits, increasing to a high of 3700 ppm in the Cu-rich stringers at Levack West (Table 13.2). Naldrett *et al.* (1982) suggested that this was due to it becoming concentrated in the residual as sulphide melted fractionate zinc-free minerals.

Lead is visible as galena in rare, cross-cutting veins whose age is about 1.2 Ga (Ulrych and Russel 1964). These are not responsible for the Pb in the samples under discussion here; the provenance of this Pb is probably extremely small specks of galena that are sometimes seen in association with chalcopyrite. Like

Zn, Pb is found in the ores at about the levels at which it is concentrated in rocks, so, again no attempt has been made to recalculate the data for Pb to that in 100% sulphides. It is seen from Table 13.2 that the North Range deposits are somewhat richer in Pb, averaging around 30 ppm in comparison with a 15 ppm average for the South Range deposits. Also, like Zn, Pb shows a tendency to follow Cu and is enriched in the Cu-rich stringers.

As and Sb

Most samples of the Levack West deposit analyzed contain As and Sb at concentrations below detection limits, which vary from sample to sample, but average about 3 ppm for As and 1 ppm for Sb. The Little Stobie Numbers 1 and 2 deposits are much richer in As, averaging 160 and 93 ppm respectively, but Sb is below the detection limit. The high As concentrations of the South Range are consistent with observations mentioned above, that while As-bearing sulfosalts such as gersdorffite, niccolite, and maucherite are commonly observed in the South Range deposits, they are extremely rare on the North Range deposits.

Se

Selenium data are reported as S/Se ratios in Table 13.2. These average about 4000, which is within the range expected of deposits of magmatic origin. Because massive sulphide contains about 36 wt% sulphur, this ratio corresponds to about 90 ppm Se in massive ore.

PLATINUM GROUP ELEMENTS and Au

PGE and Au data, averaged and recalculated to 100% sulphide, are given in Table 13.2. In conformity with established practice, the data are illustrated (Figures 13.6 and 13.7) by normalizing the values in Table 13.2 with respect to average concentrations in C1 chondrites, also given in the table.

In Figure 13.6, the ranges in average values for the Levack West, and Little Stobie Numbers 1 and 2 deposits, are compared with those for Strathcona and Falconbridge deposits. The first 3 deposits show the steeply sloping profile reflecting the high (Pt + Pd)/(Ru + Ir + Os) ratio, which is typical of deposits related to gabbroic magmas. The range in average values for the Strathcona deposit shows a similar steep profile, but the absolute concentrations are only 1/3 to 1/10 of those at the Levack West Mine. This is somewhat unexpected in view of the close physical proximity and geological similarity of the 2 deposits, although it is consistent with the lower Ni and Cu concentrations reported for the Strathcona Mine.

The Falconbridge deposit is also unusual because the Os, Ir, Ru, and Rh levels are similar to the richest reported for Sudbury to-date (Little Stobie Number 2),

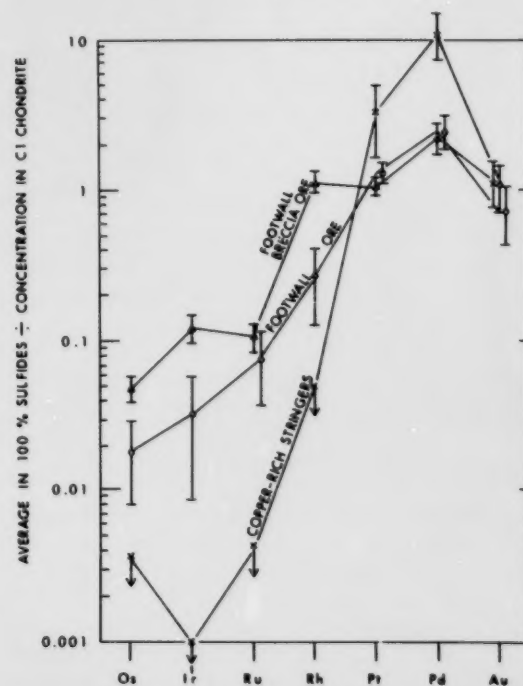
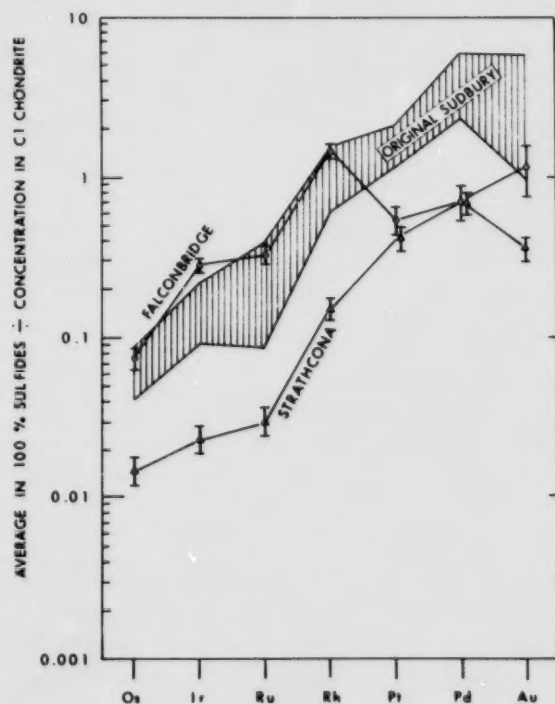
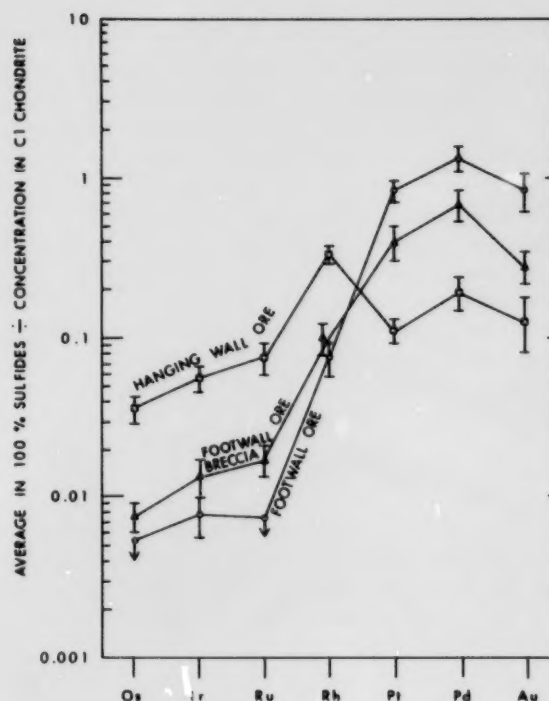
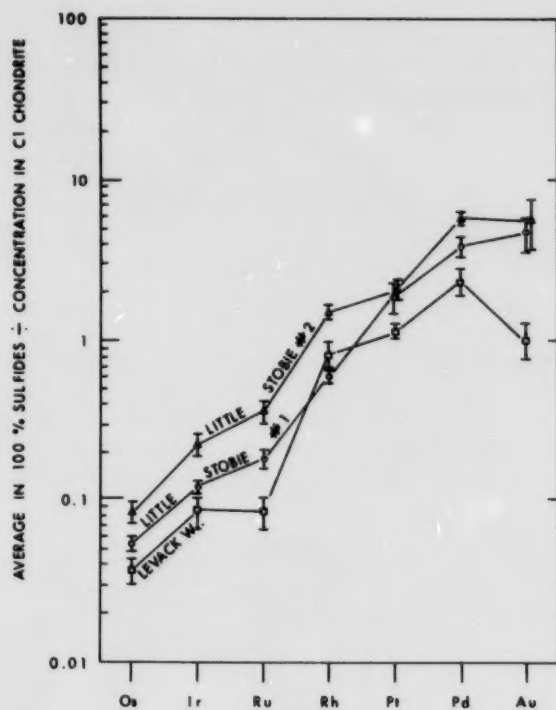


Figure 13.6. Average chondrite normalized concentrations of PGE and Au originally in the sulphide fraction of (A) the Little Stobie Numbers 1 and 2 and Levack West deposits (Hoffman *et al.* 1979); and (B) the Strathcona and Falconbridge deposits. The area labelled "Original Sudbury" in (B) is the area occupied by the data from (A). The vertical bars illustrate the extent of the mean value, plus and minus the standard error of the mean, also chondrite normalized (after Naldrett *et al.* 1982).

Figure 13.7. (A) Average chondrite-normalized concentrations of PGE and Au originally in the sulphide fraction of the hanging-wall ore, Footwall Breccia ore, and Footwall ore at the Strathcona deposit. The arrows pointing down signify that the values plotted are maximum values. (B) Average chondrite-normalized concentrations of PGE plus Au originally in the sulphide fraction of the Footwall Breccia and Footwall ores and the Copper-rich stringers associated with the Footwall ore at Levack West (data from Hoffman *et al.* 1979). (after Naldrett *et al.* 1982).

yet the concentrations of Pt and Pd are low, approaching those of the Strathcona deposit.

The data also define a pronounced zoning of PGE and Au within the Strathcona and Levack West deposits, which parallels that already described for Ni and Cu (Table 13.2), and which also conforms with that shown by the individual mineral separates analyzed by Keay and Crocket (1970). The zoning for the Strathcona deposit is illustrated in Figure 13.7a. The Footwall Breccia ore shows the sloping profile $((\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os}) = 34)$ similar to, but somewhat steeper than that typical for Sudbury. The Footwall ore shows an even steeper profile with a $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ of > 134 . On the other hand, the hanging wall ore has an unusually shallow slope with a $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ ratio of only 2.2. The 1 sample of the Cu zone, deep in the Footwall, was extremely depleted in PGE and Au, so much so that it was only possible for Naldrett *et al.* (1982) to place maximum limits on the Rh, Ru, and Os concentrations. The exact slope of the profile is therefore uncertain, although it is clearly steep.

Zoning for the Levack West deposit is shown in Figure 13.7a. Parallel changes in the same metals between the Footwall Breccia and Footwall ore to those in the Strathcona deposit are present. The Cu-rich stringer ore in the Levack West deposit appears to be a natural continuation of this process, with all metals following their typical trends, except for Ni, which decreases, and perhaps Ru and Os for which precise results are not available.

Although ore equivalent to that in the hanging wall of the Strathcona deposit is not mined and was not sampled at the Levack West Mine, the zoning in PGE and Au is similar to that found in the Footwall Breccia and Footwall ore zones at the Strathcona deposit, as seen in Figure 13.7b. The analogy between the slopes of the profiles of the 2 Footwall Breccia-hosted ores and between the 2 Footwall ore zones is remarkable.

SULPHUR ISOTOPE RATIOS

The average value of $\delta^{34}\text{S}$ varies from 0.46 at Little Stobie Number 2 to 2.71 at the Levack West Mine, well within the magmatic range.

Discussion

ZONING AT THE STRATHCONA AND LEVACK WEST MINES

Naldrett *et al.* (1982) have considered a number of models to explain the progressive increase in Ni, Cu, Zn, Pd, and Au, and decrease in Co, Ru, Ir, and Os that has been documented for the sequence; hanging wall ore, Footwall Breccia ore, Footwall ore, Cu-rich stringers. These authors concluded that only one process can account for all of the observations, namely

fractional crystallization of a monosulphide solid solution (Mss) from a sulphide melt, with the lower melting point constituents, and those less compatible in the Mss structure than in the melt, becoming enriched in the melt. Hawley (1965) first suggested this model to explain the Fe-Cu-Ni zoning at the Frood deposit, and it was subsequently favoured by Keays and Crocket (1970) and Chyi and Crocket (1976) to account for the zoning at the Strathcona Mine.

In support of their model, Naldrett *et al.* pointed out that the composition of the ore is such that Mss would be the first mineral to crystallize. Liquidus relations in the Fe-Ni-S and Cu-Fe-S systems (Kullerud *et al.* 1969) indicated that, although Ni and Cu would substitute in the Mss, both would be more concentrated in the liquid. Fractional crystallization of the initial sulphide melt would, therefore, give rise to a liquid significantly enriched in these metals. The increase in the $\text{Cu}/(\text{Cu} + \text{Ni})$ ratio toward the Footwall that is present at the Strathcona and Levack West Mines requires that Cu favour the liquid over the Mss to a greater degree than Ni. This is consistent with data on the Fe-Cu-Ni-S system (Craig and Kullerud 1969). The depletion in the absolute Ni content of the Levack West Cu-rich stringers with respect to the Footwall ore requires that as the residual liquid becomes richer in Cu, there is a reversal in the tendency for Ni to favour the liquid and that it begins to favour the Mss structure. This is again consistent with Craig and Kullerud's study; they reported that at 850°C , the sulphide liquid contained much more Cu and less Ni than the co-existing Mss.

It has been stressed previously that oxygen would also become enriched in the fractionating liquid. The Footwall ore at the Strathcona Mine is significantly richer in magnetite than the Footwall Breccia ore zone (Naldrett and Kullerud 1967), which is consistent with it being more fractionated.

The fractional crystallization model carries implications with respect to the preference of other metals for the sulphide melt versus the Mss structure. Apart from Ni and Cu, the observed zoning indicates that Pt, Pd, Au, and Zn should also prefer the sulphide liquid, and Co, Rh, Ru, Ir, and Os, the Mss structure. Studies by Skinner *et al.* (1976) on the Fe-Pd-S and Fe-Pt-S systems are consistent with the requirement that Pd and Pt should become enriched in the residual liquid.

In their work on platinum group elements in the Fe-Ni-S system, Distler *et al.* (1977) have studied the distribution of Pd, Rh, and Ru, between Mss and a Ni-rich residual liquid lying on the sulphur-deficient side of the Mss. Their data provide evidence that Pd is preferentially concentrated in the liquid, and Rh and Ru in the Mss, the latter more strongly than the former. In view of the chemical similarities of Pt with Pd, and Ir and Os with Ru, Pt is likely to enter the liquid preferentially and Ir and Os the Mss.

The small amount of relevant experimental data available on Co (Kuznetsov *et al.* 1966) and on Zn (Kullerud 1953) indicate that the former should be concentrated in the Mss, and that the latter should concentrate in the residual liquid, again in accord with the observations.

It appears, therefore, that all of the relevant experimental data support fractional crystallization as the explanation of the zoning.

FALCONBRIDGE

As shown in Figure 13.6a, the Falconbridge deposit has a flat PGE profile, almost identical in shape (although not in concentration) to that for the hanging-wall ore of the Strathcona deposit. When the flat profile is coupled with the relatively high Co content (0.22 wt %) and low Cu/(Cu + Ni) ratio (0.22), analogy with the Strathcona deposit suggests that the ore sampled by Naldrett *et al.* (1982) at the Falconbridge Mine represents an early crystallized fraction, and that Cu, Pt, Pd, Au-rich ore, amounting perhaps to as much as twice that already sampled, and equivalent to the Footwall Breccia and Footwall ore at the Strathcona Mine, was not sampled.

Naldrett *et al.*'s (1982) samples were collected to be as representative of the orebody as possible, given the current accessibility at the mine, and were distributed from the 100 to the 1600 m levels. Considering the whereabouts of the missing ore, they investigated the possibility that, during its original emplacement, the

ore magma moved vertically up the fault, crystallizing and differentiating on the way, so that the early crystallizing fraction remained behind at depth and the late crystallizing Cu, Pt, and Pd-rich part solidified at higher levels from whence it has been removed by erosion. If this were true, a systematic increase in the $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ ratio upward through the preserved part of the deposit would be expected. No such variation is present as is seen from Figure 13.8 Naldrett *et al.* favoured a second possibility (Figure 13.9) that the Falconbridge deposit originally resembled that at the Strathcona deposit and also that at the Creighton Mine, where the $\text{Cu}/(\text{Cu} + \text{Ni})$ ratio increased away from the norite into an embayment in the Footwall. They suggested that, at the Falconbridge Mine, post-ore faulting (also evident at the Creighton Mine) removed the embayment, leaving the Cu, Pt, Pd-depleted part to become remobilized along the fault. The location of the missing ore would depend on the net movement that occurred along the fault.

Controls on the Compositions of Deposits

It has been shown that certain marked compositional differences exist between different Sudbury deposits. As discussed above, some of these may be the result of incomplete preservation or the incomplete sampling of a zoned deposit. Other differences cannot be explained in this way. For example, with respect to the 2 nearby deposits of Levack West and Strathcona, the

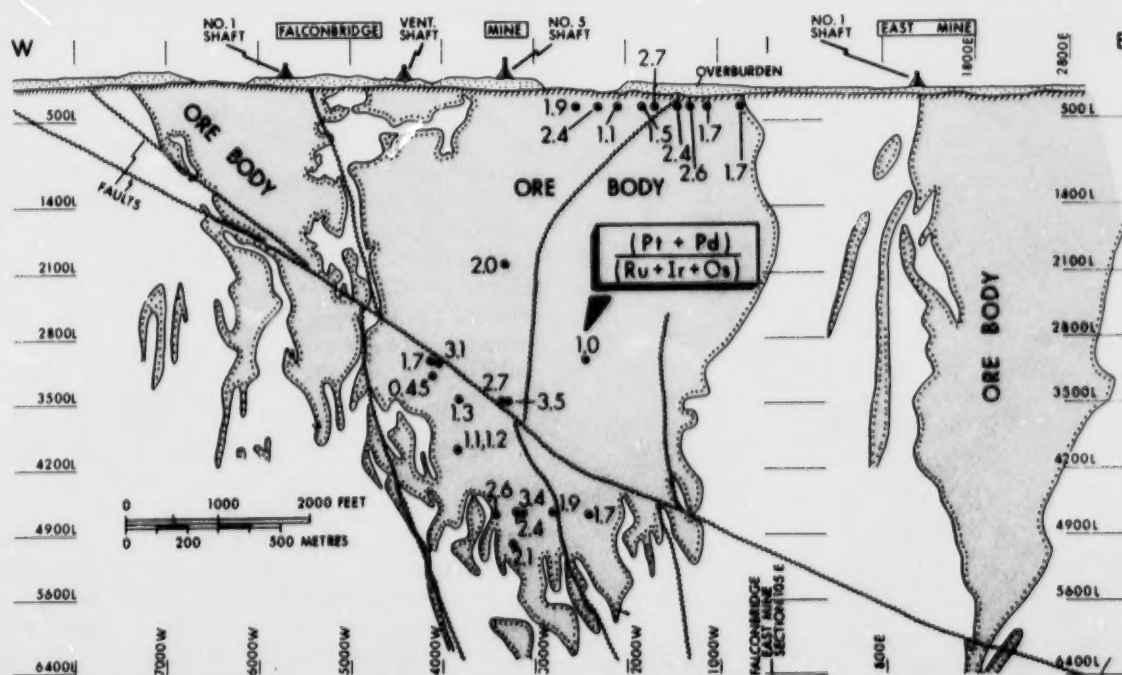


Figure 13.8. Vertical longitudinal section through the Falconbridge orebody in the plane of the main fault. The locations of the samples analyzed are shown, together with their (Pt + Pd)/(Ru + Ir + Os) ratios (after Naldrett *et al.* 1982).

sulphide liquid responsible for the former apparently contained 50% more Ni and Cu, 3 times as much of each of the PGE, and about the same amount of Co as that responsible for the latter. Of the 2 immediately adjacent deposits of Little Stobie Numbers 1 and 2, the former contains approximately 2/3 of the PGE of the latter. There are also significant differences between the Little Stobie group of deposits and the Levack West Mine, with the former containing 2 to 3 times the PGE and rather less Ni than the latter.

The composition of sulphide ore segregating from a silicate melt is closely related to the composition of the silicate melt. Interaction between the 2 in a number of different ways can cause the composition of the magma and hence of the sulphide to vary. Duke and Naldrett (1978) have shown how the fractional crystallization of mafic and ultramafic magmas under sulphide-saturated and sulphide-unsaturated conditions can produce quite different compositional trends. Campbell and Naldrett (1979) and Naldrett (1979) have shown how strongly the amount of sulphide liquid that reaches equilibrium with a given body of magma can affect both the absolute concentrations and the ratios of the different metals, depending on their respective partition coefficients between sulphide and silicate liquids.

Precise modelling of metal distributions is hampered by imprecise knowledge of the partition coefficients

of metals between sulphide and silicate melts, although Rajamani and Naldrett (1978) indicated that values of 275 for Ni, 250 for Cu, and 80 for Co were appropriate. A value of 1500 has also commonly been used for Pd (see Naldrett *et al.* 1979 for a discussion).

The causes of sulphide segregation from silicate melts are numerous, although in the case of Sudbury, Irvine (1975) suggested that this segregation was the result of the assimilation of siliceous country rocks. Naldrett *et al.* (1982) suggested that the assimilation of varying amounts of siliceous country rock could cause the segregation of varying proportions of sulphide that was dissolved in the magma. These authors considered the Strathcona and Levack West deposits, and assumed that a magma not quite saturated in the sulphide, containing 0.15 wt% sulphur, (a reasonable assumption made on the basis of the experiments of Haughton *et al.* 1974), 210 ppm Ni, 150 ppm Cu, 20.8 ppm Co, and 1.2 ppb Pd, was intruded in the vicinity of the 2 deposits, became contaminated with siliceous country rocks to cause the segregation of 5% of the total dissolved sulphide at the Levack West Mine and 50% at the Strathcona Mine. The resulting compositions, modelled as described by Campbell and Naldrett (1979), are compared with the observed compositions in Table 13.3. The match is quite close.

The same exercise was performed for the Little Stobie Numbers 1 and 2 deposits, where it was necessary to assume an initial magma containing 150 ppm Ni, 181 ppm Cu, 21.5 ppm Co, and 2.41 ppb Pd. Model compositions, based on the segregation of 2.5% of the available sulphide at deposit 2, and 12% of the available sulphide at deposit 1, are also compared with the observations in Table 13.3.

Naldrett *et al.* (1982) also showed that the 2 quite different magma compositions, necessary to explain the North and South Range deposits, could have been derived from the same source magma if it had precipitated some olivine before giving rise to the South Range deposits, and if it had precipitated sulphide on 2 separate occasions prior to giving rise to the Strathcona and Levack West deposits on the North Range. Presumably, these earlier sulphide precipitates are deposits that remain to be discovered at depth. Figure 13.10 is a schematic flow diagram of this model.

Naldrett *et al.* stressed that numerous other combinations of the basic steps could account for the observed variability. These authors noted that it was likely that what are shown as a series of discrete equilibrium steps in Figure 13.10, would occur as a continuum in nature, with a new event starting before the last had finished. The essential point is that it is possible to devise a scenario to explain the variability in composition that is observed at Sudbury on a magmatic basis, starting with realistic magma compositions.

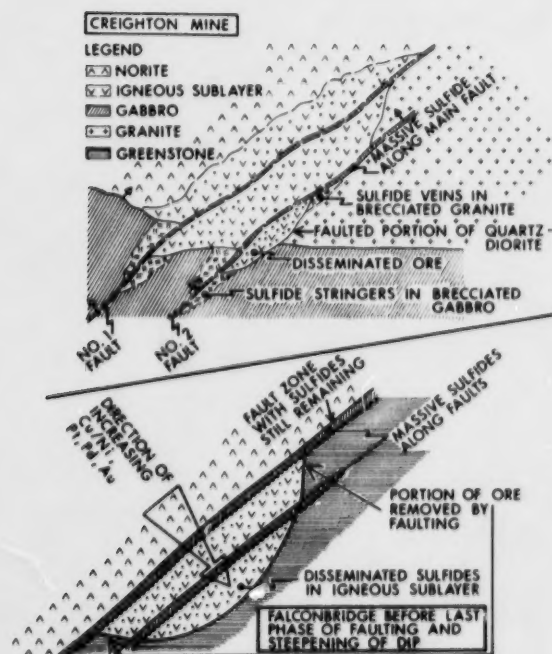


Figure 13.9. Vertical section through the Creighton deposit (after Yates 1948) compared to a reconstruction of the Falconbridge deposits as it may have looked originally (after Naldrett *et al.* 1982).

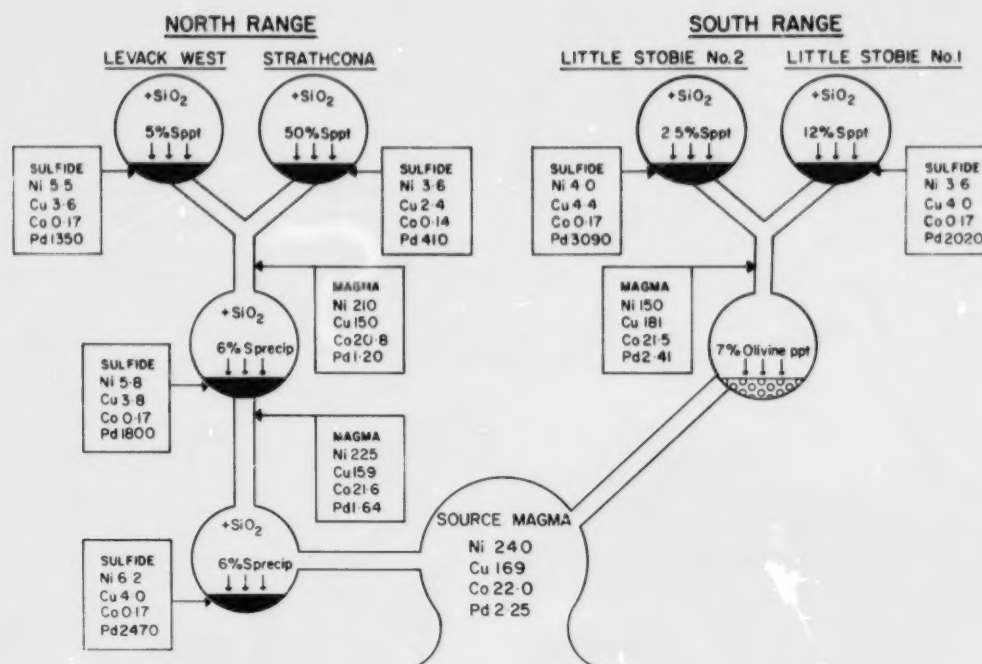


Figure 13.10. Flow sheet illustrating the effect of fractionally crystallizing olivine (in the first event contributing to the South Range ore) and of abruptly segregating a given percentage of the sulphide dissolved in the magma (in all other cases) on the composition of a possible source magma for Sudbury, and on the sulphides segregating from it. The combination of these sequences of events can give rise to ores with compositions closely resembling those estimated for Levack West, Strathcona, and Little Stobie Numbers 1 and 2, with the exception of their Cu content. The abrupt precipitation of sulphide is envisaged as the consequence of mixing of magma with silica-rich material (after Naldrett *et al.* 1982).

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CHAPTER 14

Ore Deposits of the North Range, Onaping-Levack Area, Sudbury

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CHART B

Plan 1 Geological plan, 1475 Level, Onaping-Levack area

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ABSTRACT

Ore deposits in the Onaping-Levack area of the North Range occur in Sublayer intrusions marginal to the Sudbury Igneous Complex, in underlying zones of Footwall Breccia, and at various distances from the contact in the Footwall. The Archean Footwall rocks in this area consist in part of a calc-alkalic layered igneous complex composed of a wide variety of rock types ranging in composition from granodioritic to ultramafic. The predominant rock types are hypersthene tonalite and anorthositic norite. A contact thermal metamorphic aureole, extending for 1 km into the Footwall rocks, is composed of the pyroxene hornfels, hornblende hornfels, and albite-epidote hornfels zones. Plagioclase recrystallization and the first appearance of metamorphic clinopyroxene determine the extent of the hornblende hornfels zone, which at the Strathcona Mine is 600 m in width. The pyroxene hornfels zone extends up to 250 m from the norite contact, and includes along the innermost part, a zone of brecciated rocks termed the Footwall Breccia. This unit originated by partial melting of leucocratic layers in the complex, and resulted in the fragmentation of more refractory anorthositic, mafic, and ultramafic layers.

A high percentage of the North Range ore occurs in Footwall Breccia, the greatest development of which is spatially related to embayment structures characterized by pronounced thickening of the Sublayer. Deep Footwall ore and copper-rich vein deposits occur in fractured, but nonbrecciated Footwall rocks.

The ore deposits exhibit a distinct pattern of metal zonation, with Cu, Ni, Pt, Pd, Ag, and Au increasing in the ore outward and away from the contact. A re-

verse trend is indicated for the metals Co, Rh, Ru, Ir, and Os. The ores were introduced as an immiscible sulphide-rich liquid, carried by Sublayer magma. The observed metal zonation is the consequence of the fractionation of the sulphide melt, primarily due to the crystallization of monosulphide solid solution, with the residual liquid being progressively expelled into the Footwall and away from the contact.

INTRODUCTION

The Onaping-Levack area is located on the northwestern margin of the Sudbury Igneous Complex and covers a 10 km belt extending across Levack Township. Commonly referred to as the North Range deposits, the orebodies in this area occur along the lower contact of the Complex and at various depths within Footwall rocks. Outcrops containing sulphide mineralization were first discovered in Levack Township in 1888 on property that is presently part of the Levack Mine. The first recorded production of Ni-Cu ore in the Onaping-Levack area was from this deposit in 1913. All current and past-producing mines, as well as undeveloped deposits in the Onaping-Levack area, are located on Figure 14.1 and listed in terms of ownership and production dates in Table 14.1. Total past production and presently known ore reserves for the district are in excess of 200 million tons.

GENERAL GEOLOGY

In Levack Township, rocks of the Sudbury Igneous Complex strike generally northeast and dip southeast

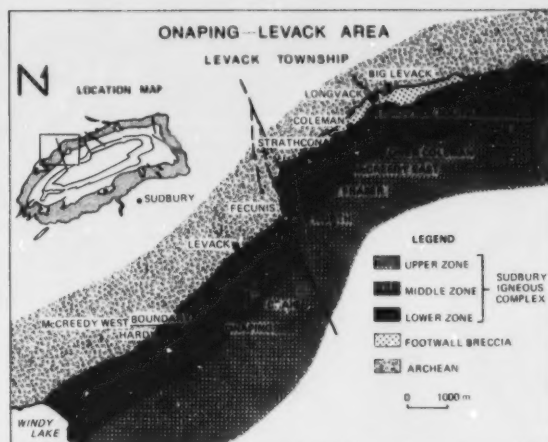


Figure 14.1. Geological location plan of the ore deposits in the Onaping-Levack area of the North Range.

at about 40° toward the centre of the basin. The entire Complex has a total thickness at surface of between 2.5 to 3.0 km. Lateral continuity of the Complex is disrupted by a large number of faults, the most important of which are the Fecunis Lake and Bob's Lake Faults. The Fecunis Lake Fault, which has a total length in excess of 300 km, outcrops immediately to the west of the Fecunis Mine (Figure 14.1). This fault strikes $N20^\circ W$,

dips $70^\circ W$, and sinistrally displaces the norite contact 600 m horizontally and approximately 200 m vertically. The Bob's Lake Fault outcrops to the east of the North Mine and is considered to be a branch structure of the Fecunis Lake Fault. It dips eastward at 85° , and has laterally displaced rocks of the Sudbury Igneous Complex for about 100 m. The fault between Longvack and Longvack South Mines is one of the number of late structural disturbances in this area.

ROCK UNITS OF THE ONAPING-LEVACK AREA

The principal rock units in the Onaping-Levack area are listed chronologically in Table 14.2. Although there is some uncertainty about the age relationship of the Contact Sublayer to the Lower Zone of the Complex, it is considered here as an integral part of the Lower Zone. On the geologic sections and level plans which accompany this paper, the mafic norite of the Lower Zone is combined with the Contact Sublayer (Dark norite breccia in mine terminology) as a single unit. In the following section, however, they are described separately. The Footwall rocks and important Footwall Breccias, which contain a high proportion of the economic sulphide mineralization in the area, are described in more detail.

TABLE 14.1: ORE DEPOSITS OF THE ONAPING-LEVACK AREA.

DEPOSIT	OWNERSHIP	ACCESS	DEPTH (FEET)	PRODUCTION	
				FROM	TO
HARDY	Falconbridge	No. 1 Shaft	1427	1954	1978
BOUNDARY	Falconbridge	No. 1 Shaft	952	1961	1973
ONAPING	Falconbridge	No. 1 Shaft	4400		
		No. 2 (I)*	5348	1961	1982
MCCREEDY WEST	Inco	Ramp	1600	1973	Present
CRAIG	Falconbridge			Not Developed	
LEVACK	Inco	No. 2 Shaft	3915		
		No. 3 (I)	3716	1913	Present
FECUNIS	Falconbridge	No. 1 Shaft	3993		
		No. 2 Shaft	3243	1957	1977
NORTH	Falconbridge	No. 1 (I)	4430	1964	Present
MCCREEDY EAST	Inco			Not Developed	
FRASER	Falconbridge	No. 1 Shaft	5250	1981	Present
STRATHCONA	Falconbridge	No. 1 Shaft	3205**		
		No. 2 Shaft	3144	1968	Present
COLEMAN	Inco	No. 1 Shaft	2278	1970	1982
LOWER COLEMAN	Inco			Not Developed	
LONGVACK	Falconbridge	Open Pit		1956	1961
LONGVACK SOUTH	Falconbridge	No. 1 Shaft	1289	1968	1977
BIG LEVACK	Inco			Not Developed	

(I)* Internal shaft, depth at bottom

** Shaft deepening in progress (1984)

TABLE 14.2: ROCK UNITS IN THE ONAPING-LEVACK AREA.

Olivine diabase dikes
Diabase dikes
Footwall Breccia (Late Granite breccia)
Sudbury Igneous Complex
Upper Zone
Middle Zone
Lower Zone—Felsic norite
—Mafic norite
Contact Sublayer
Sudbury Breccia
Footwall rocks

Lower Zone of the Sudbury Igneous Complex

FELSIC NORITE

The felsic norite is a grey-coloured, medium- to coarse-grained equigranular rock with a hypidiomorphic texture. It is composed of 50 to 70% tabular plagioclase (An_{50} to An_{65}), 3 to 10% potassic feldspar, 10 to 30% pyroxene, 5 to 15% granophyre and quartz, and 2 to 5% biotite. Minor minerals present include magnetite, ilmenite, apatite, zircon, and sulphide. For most of the Lower Zone, orthopyroxene content is dominant relative to clinopyroxene and both are readily altered to hornblende, actinolite, chlorite, and talc. As the mafic mineral content increases, the felsic norite grades into mafic norite, the marginal unit of the Main Mass of the Sudbury Igneous Complex.

MAFIC NORITE

Mafic norite is dark grey to dark brown, medium- to coarse-grained equigranular, and has a hypidiomorphic texture. At lower horizons, however, the mafic norite exhibits a more poikilitic texture. It is composed of 20 to 45% tabular plagioclase (An_{40} to An_{65}), 30 to 60% subhedral hypersthene, 5 to 10% subhedral to anhedral augite, and 2 to 5% biotite. Varying quantities of actinolite, hornblende, chlorite, and epidote may be present depending on the degree of alteration of the pyroxenes. Minor minerals in the rock include quartz, granophyre, apatite, zircon, ilmenite, magnetite, and disseminated sulphide.

SUBLAYER

Distinctive mafic igneous rocks in close association with sulphide mineralization occur below the mafic norite in the Onaping-Levack area. The unit has been described from the Strathcona Mine (Naldrett and Kullerud 1967; Cowan 1968) and from the Fecunis and Fraser Mines (Hewins 1971). Souch, Podolsky *et al.* (1969) demonstrated that a close association of this

rock type with sulphides is common along the base of the Main Mass norite of the Sudbury Igneous Complex and introduced the term Sublayer. Subsequently, Pattison (1979) described Sublayer units from around the Complex and suggested intrusive emplacement prior to the Main Mass norite.

The Sublayer is a fine- to medium-grained heterogeneous rock, which commonly contains a wide variety of inclusions and matrix compositions ranging from norite, gabbro, or diorite to quartz diorite. Norite appears to be the most common matrix, consisting of 30 to 50% plagioclase (An_{40} to An_{60}), 20 to 35% subhedral to euhedral hypersthene, 8 to 15% anhedral augite, with minor amounts of biotite, magnetite, ilmenite, quartz, granophyre, apatite, and secondary minerals. Sulphide content is variable, occurring as fine disseminations or irregular blebs and stringers.

Xenoliths in the Sublayer include felsic, intermediate, and mafic rock types derived from the adjacent Footwall. In addition, the Sublayer contains a suite of ultramafic rock types whose derivation has usually been attributed to a lower, hidden ultramafic zone of the Sudbury Igneous Complex (Naldrett and Kullerud 1967; Rae 1975; Scribbins *et al.* 1984). However, recent studies indicate that the Sudbury Igneous Complex in the Strathcona area is underlain by an Archean, layered igneous complex. This Footwall layered complex includes ultramafic rocks with orthopyroxene, clinopyroxene, and olivine-bearing varieties. There remains the possibility, therefore, that some, if not the entire group of ultramafic xenoliths in the Sublayer and associated Footwall Breccias originated from this layered complex.

The Sublayer is not universally located beneath the mafic norite, but in some instances is separated from rocks of the Lower Zone by a septum of Footwall formations. It has also been observed to intrude the mafic and rarely, the felsic norite. In general, however, the greater proportion of the Contact Sublayer occurs stratigraphically beneath the mafic norite. Contact relationships of Sublayer and mafic norite are not always clear and well defined. Although usually sharp, the contact is highly irregular and there is evidence of mixing of the 2 rock types. Lower parts of the mafic norite are often fine grained, sulphide-bearing, and may contain inclusions. For these reasons, the 2 units are combined and represented as a single rock type on the accompanying level plans and sections. The contact of the Sublayer with underlying Footwall Breccias is also highly irregular and gradational.

Footwall Rocks

GENERAL ASPECTS

The term "footwall rocks" is used here to collectively identify all rock units beneath the Sudbury Igneous

Complex. Even though extensive studies of the Footwall are documented elsewhere (for example, Dressler, Chapter 6, this volume), their economic importance in the Onaping-Levack area warrants some additional description and the examination of new data. Rocks of the Footwall are readily classified into 2 principal units; Footwall Breccia and layered rocks of the basement complex from which the breccia has been derived.

Except for post-norite diabase dikes, all Footwall rocks are thermally recrystallized within the contact metamorphic aureole of the Sudbury Igneous Complex. At the Strathcona Mine, the aureole is more than 1 km wide and is subdivided into pyroxene hornfels, hornblende hornfels, and albite-epidote hornfels zones. The innermost zone adjacent to the Complex is the pyroxene hornfels zone, which has a variable width of up to 250 m. All occurrences of Footwall Breccia in the Onaping-Levack area are within this high grade contact metamorphic zone, an association which strongly suggests a genetic relationship.

The less disturbed rocks of the Footwall, outward from the Footwall Breccia, have hitherto been referred to as the Levack Gneiss Complex or simply as the feldspathic gneiss complex. It is suggested here that the heterolithic rocks of this area are part of an igneous, cumulate-textured, layered complex, the component layers ranging from a granodioritic to an ultramafic composition. The complex has a recognizable width of 2.5 km, beyond which extensive migmatization and the intrusion of granitic plutons has left little indication of what material constituted the original rocks. At many locations within the layered complex, there is also evidence of the late granitization from the presence of pegmatite veins, irregular stockworks, and small intrusive granitic bodies up to several hundred m across.

Recent geochronologic work by Krogh *et al.* (Chapter 20, this volume) on zircons from Footwall rocks in Levack Township indicate an upper intercept age of 2711 ± 7 Ma and a lower intercept age of 1836 ± 14 Ma. Krogh *et al.* (Chapter 20, this volume) interpret the upper age as being the primary crystallization age, while the lower age is attributed to resetting by shock metamorphism. Newly grown zircons with an age of 1850 Ma occur in a Footwall rock sample adjacent to the norite contact.

LAYERED BASEMENT ROCKS

The most common rock type of the Archean layered complex is hypersthene quartz diorite. It is a fine- to coarse-grained, light grey rock with well-developed rhythmic layering. Typically, preserved pre-metamorphic textures are sub-ophitic, consisting of hypidiomorphic pyroxene partly embedded in orthocumulus plagioclase. As the quartz content decreases, these

rocks grade into diorites and more mafic rocks such as norites and gabbros. As the plagioclase content increases and the quantity of ferromagnesian minerals decreases, norites grade to anorthositic norites and anorthosites. The latter are white, creamy white, or pinkish white, medium- to coarse-grained, usually massive rocks with allotriomorphic textures. The composition of plagioclase in the anorthosites is in the range An_{35} to An_{55} and is accompanied by antiperthite and up to 10% quartz. Anorthositic rocks form broad distinctive zones within the complex, similar to melanocratic varieties of norite, gabbro, and associated ultramafic rocks. The conspicuous layers of ultramafic rocks occur in the deepest levels at the Fraser and North Mines. The largest is 140 m thick, extending laterally for a distance of over 1 km at a distance of between 60 to 200 m from the margin of the Sudbury Igneous Complex. This body is compositionally layered with units of dunite, orthopyroxene, and clinopyroxene-bearing peridotites and pyroxenites. Orthopyroxenite, clinopyroxenite, and websterite often contain plagioclase, and grade into melanocratic varieties of norite and gabbro with or without olivine. These in turn grade into anorthosite gabbro and anorthosite. Quartz-rich units of the complex include hypersthene-bearing varieties of granodiorite and quartz-monzonite.

Chemical analyses of representative rock types from the Footwall complex are listed in Table 14.3. Except for pyroxene-rich ultramafic varieties, the analyses plot in the calc-alkalic field on AFM and Jensen diagrams (Figure 14.2); and exhibit a well-defined differentiation trend. Additional plots of analyses of Footwall Breccia on Figure 14.2 will be referred to in a subsequent section. The presence of original hypersthene in most units of the complex, abundant apatite, and general calc-alkalic affinity, strongly suggests that these rocks constitute a charnockite-anorthosite graduated series as described by Hödal (1945) and Middlemost (1970).

SUDBURY BRECCIA

Sudbury Breccia is recognized in all Footwall rocks throughout the Onaping-Levack area. It occurs as dikes, stringers, and irregularly-shaped bodies of pseudotachylite, and is most commonly developed along the contacts of 2 contrasting lithologies. It is characterized by a fine-grained to aphanitic matrix containing locally derived rock fragments. The matrix is composed of finely comminuted rock flour with a chemical composition approximating that of the host rock to the breccia (Speers 1957; Dressler, Chapter 6, this volume). Beyond the influence of contact thermal metamorphism, from the Sudbury Igneous Complex, the breccia matrix is black, but becomes lighter coloured and coarser grained with increasing thermal recrystallization. Greenish grey fragments of Sudbury

TABLE 14.3: CHEMICAL ANALYSES OF REPRESENTATIVE FOOTWALL ROCKS.

SAMPLE NUMBER	1	2	3	4	5	6	7	8	9	10
Major Oxides ^a										
SiO ₂	71.4	65.7	64.9	62.5	60.1	58.6	53.4	51.5	48.6	43.7
TiO ₂	0.17	0.31	0.53	0.43	0.62	0.48	0.94	1.12	0.85	1.62
Al ₂ O ₃	14.8	17.7	15.8	17.3	15.8	21.1	16.3	16.0	9.98	10.1
Fe ₂ O ₃	0.77	0.67	1.34	1.36	2.38	1.27	3.23	4.27	3.89	3.33
FeO	0.50	1.30	2.90	2.40	3.40	1.10	5.40	5.60	6.90	9.00
MnO	0.01	0.03	0.08	0.05	0.10	0.03	0.14	0.15	0.18	0.18
MgO	0.46	0.77	2.58	1.99	3.54	0.84	4.42	4.95	11.8	12.8
CaO	2.71	4.26	4.73	4.79	6.77	5.94	8.11	8.18	11.3	11.6
Na ₂ O	4.32	5.53	4.79	5.63	4.67	6.44	4.33	4.18	1.29	1.51
K ₂ O	2.20	1.19	0.74	1.07	0.82	1.16	0.83	0.93	2.24	0.98
P ₂ O ₅	0.04	0.08	0.09	0.14	0.08	0.47	0.30	0.47	0.81	0.17
CO ₂	0.1	0.2	0.3	0.1	0.2	0.1	0.2	0.1	0.1	0.1
S	Nil	Nil	0.09	0.07	0.03	Nil	Nil	0.09	0.21	0.09
Total	97.48	97.74	98.87	97.85	98.61	97.53	97.60	97.54	98.15	95.18
L.O.I. ^b	0.77	0.70	0.77	0.93	0.47	0.93	0.77	0.70	1.08	1.08
Trace Elements ^c										
Cr	163	110	185	156	157	82	116	157	684	274
Cu	6	250	15	200	48	13	46	58	130	38
Ni	8	9	40	34	63	9	34	42	140	42
Pb	8	16	4	4	2	4	8	8	4	4
Rb	10	0	10	20	10	20	0	10	150	10
Sr	530	550	480	640	560	770	470	540	230	280
Zn	14	31	27	35	31	21	39	52	72	25
Zr	70	90	210	110	50	230	90	80	170	50

Notes: a weight %
 b loss on ignition
 c in ppm

1. Opx. granodiorite (opdalite)
2. Opx. granodiorite (opdalite)
3. Opx. tonalite (enderbite)
4. Opx. tonalite (enderbite)
5. Opx. diorite (jolunite)
6. Anorthosite
7. Norite
8. Anorthositic norite
9. Glomeroporphyritic melagabbro
10. Pyroxenite

Analyst: X-Ray Assay Laboratories, Don Mills, Ontario

Breccia are identified in the Footwall Breccia beneath the norite. This confirms its time of origin as prior to the intrusion of the Sudbury Igneous Complex.

DIABASE INTRUSIONS

Several varieties of diabase crosscut the rocks of the area. Pre-Sudbury Igneous Complex diabase is a massive, fine- to medium-grained, dark green to black rock with an equigranular or glomeroporphyritic texture. It forms north-northeast- to northwest-trending dikes up to 7 m wide and usually displays chilled margins. The glomeroporphyritic variety resembles Matachewan Diabase which has been dated at 2485 Ma (K/Ar whole rock, Wanless *et al.* 1965) and 2690 ± 93 Ma (Rb/Sr whole rock, Gates and Hurley 1973). These dikes are thermally recrystallized within the metamorphic aureole and are broken into trails of fragments in the zone of the Footwall Breccia. Post-Sudbury Igneous Com-

plex intrusions consist of east-trending quartz diabase dikes and northwest-trending olivine diabase dikes. The former is cut by the latter, which has been dated in the range from 1245 Ma (Van Schmus 1965) to 1460 ± 130 Ma (Gates and Hurley 1973). The olivine diabase belongs to the Sudbury dike swarm and represents the youngest magmatic activity in the area.

CONTACT METAMORPHIC AUREOLE

Thermal recrystallization within the contact metamorphic zone is evident in all rock types. In the pyroxene hornfels zone, layered rocks of felsic to ultramafic composition are characterized by the following metamorphic assemblages:

Plagioclase - quartz - potassic feldspar ± orthopyroxene

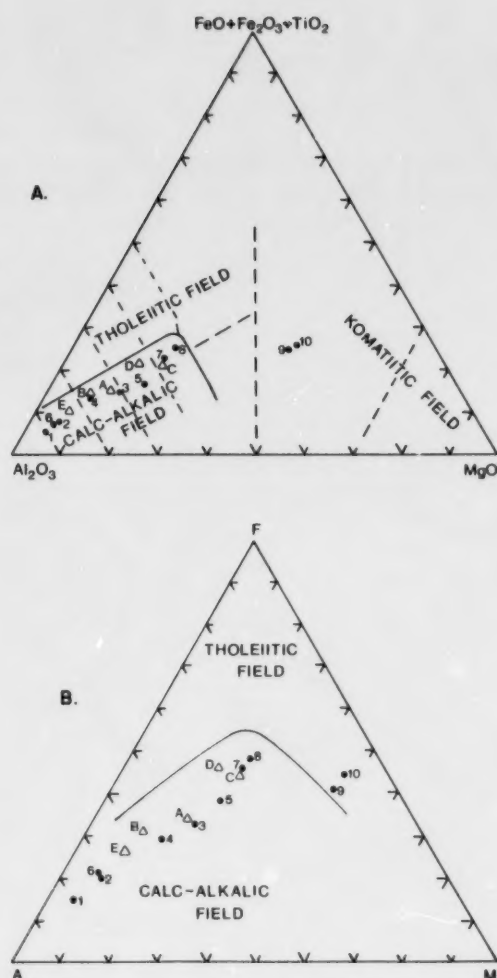


Figure 14.2. Compositional plots of selected representative Footwall Rocks (dots) and matrix from Footwall Breccias (triangles). Numbers and letters refer to analyses of Tables 14.3 and 14.4, respectively. A-Jensen, B-AFM.

Plagioclase $\pm$ orthopyroxene - quartz - potassic-feldspar

Orthopyroxene - plagioclase $\pm$ quartz - potassic-feldspar

Clinopyroxene - plagioclase $\pm$ quartz - potassic-feldspar

Orthopyroxene - clinopyroxene - plagioclase $\pm$ quartz - potassic-feldspar

Olivine - orthopyroxene - clinopyroxene $\pm$ plagioclase

It is beyond the scope of this paper to review in detail the modal and textural diversity of all rock compositions in the layered complex. A few typical examples will suffice to illustrate the thermal metamorphism within the contact aureole. Hypersthene quartz diorite or leucocratic quartz norite consists of

fine crystalloblastic mosaics of pleochroic hypersthene and less abundant augite, both of which have recrystallized from original subhedral tabular pyroxenes. The pyroxene mosaics are interlocked with, or enveloped by, mosaics of stubby plagioclase crystals with well-developed Carlsbad twinning. These mosaics retain the shape of the original prismatic plagioclase grains from which they have recrystallized. The quartz content is as high as 20% and is present in lenses of interlocking polygonal grains. Minor microperthite and dark red biotite are occasionally present and euhedral apatite and minor zircon are consistent accessories. Anhydrous magnetite, ilmenite, and their intergrowths are associated with the pyroxene mosaics. The megascopic layering in these rocks results from rhythmically alternating concentrations of pyroxenes with feldspathic or quartzofeldspathic layers. Although the proportions of these constituents are highly variable, the original hypidiomorphic granular and ophitic textures are preserved in spite of complete recrystallization.

The transition from pyroxene hornfels to the hornblende hornfels zone is determined by the gradual disappearance of metamorphic orthopyroxene. Rock types in this zone are similar to those of the pyroxene hornfels zone, except for a slightly more altered appearance due to the presence of amphiboles. The typical metamorphic assemblage of this zone is hornblende - augite - plagioclase $\pm$ biotite - quartz - potassic-feldspar, with large variations of the mineral proportions depending on original composition of individual layers. Unrecrystallized primary hypersthene is the dominant pyroxene of the zone and, although it is generally altered to talc and amphibole, it is readily identifiable by its euhedral form. Augite occurs as mosaics of xenoblastic crystals which have recrystallized from original, but highly altered tabular clinopyroxene. In more mafic and ultramafic units of the Complex, dark brown hornblende with relict diallage partings and reddish brown poikiloblastic biotite are common constituents. Epidote is also present in appreciable amounts in ultramafic rock. Euhedral pseudomorphed garnets have been identified in some dioritic and anorthositic units. Similar to the pyroxene hornfels zone, plagioclase and quartz are completely recrystallized into fine-grained crystalloblastic mosaics.

The albite-epidote hornfels zone is recognized by the disappearance of metamorphic augite and the gradual reduction in plagioclase recrystallization. This occurs at about 600 m from the contact in the Strathcona Mine. Orthopyroxene is still the dominant mafic mineral, but clinopyroxene may also be present. Both pyroxenes are usually strongly altered to a mixture of amphibole, biotite, chlorite, talc, and epidote, and their original character is sometimes obscure. Plagioclase is strongly saussuritized, and the crystal rims are

replaced by albite. Textures indicate that in most rocks, plagioclase is a cumulus phase. Euhedral apatite is particularly abundant in pyroxenitic and anorthositic rocks.

The outward limit of contact thermal metamorphism in the Onaping-Levack area is not fully established. Beyond 1 km from the contact, Footwall rocks exhibit features of cataclastic deformation and weak regional metamorphism. As discussed elsewhere in this Volume, deformation lamellae in quartz and plagioclase, kink bands in biotite, and undulatory extinction of pyroxene have been attributed to severe shock metamorphism.

FOOTWALL BRECCIA

Footwall Breccia constitutes a discrete, but irregular and discontinuous zone of variable width between the Sublayer and the undeformed, but recrystallized units of the Footwall layered complex. These breccias have been the subject of extensive debate among Sudbury geologists and the object of considerable research by a number of workers, among them Mitchell and Mutch (1957), Naldrett and Kullerud (1967), Cowan (1968), Greenman (1970), Hewins (1971), Hebil (1978), Pattison (1979), and Dressler (Chapter 6, this volume).

Footwall Breccia, synonymous with "leucocratic breccia, granite breccia or late granite breccia" in mine terminology, occurs adjacent to the Sublayer contact on the innermost side of the pyroxene hornfels contact metamorphic zone. It is highly heterogeneous in composition, consisting of a fine- to medium-grained matrix with a variety of inclusions of differing shape, size, and mineralogy. Characteristically, the inclusions represent Footwall rocks from the layered complex and include anorthositic, intermediate, mafic, and ultramafic varieties. At some locations, inclusions of Sudbury Breccia, diabase, and mafic norite have been recognized. The breccia matrix is light to dark grey, fine to medium grained, and has a granophyric or poikiloblastic texture. It consists of lath-shaped zoned plagioclase crystals (An_{32} to An_{45}) with both Carlsbad and albite twinning, intermixed with smaller, stubby, sometimes saussuritized plagioclase grains, poikilitically enclosed in large anhedral grains of quartz. Modal quartz content in some of the breccia matrix may reach 40%.

The proportion of quartzofeldspathic matrix in the breccia increases toward the norite contact, and at its maximum development, the rock is essentially a granophyre containing scattered inclusions and a variable sulphide content. Contacts between the matrix and anorthositic, mafic, and ultramafic fragments are generally sharp, whereas inclusions of felsic to intermediate composition show strong evidence of assimilation and their contacts are diffuse and gradational. Many inclusions are subrounded and may be elongated parallel to dynamofluidal textures in the ma-

trix, suggestive of a condition of plastic flow. Footwall Breccias at some localities, specifically of the Longvack South, Strathcona, and Hardy Mines contain rare, discrete sulphide fragments, with either rounded or angular outlines, similar to those described by Pattison (1979). Some of these fragments contain mafic silicate minerals in a textural relationship similar to that observed in mineralized Sublayer norite. A derivation from this source is considered highly probable. Xenocrysts of pyroxene and large corroded iabradorite grains in the breccia matrix are considered by Hewins (1971) to have originated from the mafic norite. Leucocratic breccia of this type is referred to as grey breccia by Greenman (1970) and is an important host for sulphide mineralization on the North Range.

The character of the Footwall Breccia gradually changes with distance outward from the contact with the enveloping rocks. Fresh pyroxene becomes more abundant accompanied by a reduction in quartz, lath plagioclase, and potassic feldspar. Inclusions are less altered and more readily identifiable to rock units of the layered complex. Irregular, highly digested fragments of Sudbury Breccia are increasingly common, but sulphide mineralization and inclusions derived from the Sudbury Igneous Complex are absent. Greenman (1970) referred to this as barren breccia. With gradual but progressive reduction in the amount of "flood" character of quartz, which is replaced by interstitial grains and lenses of polygonal grains and increasing quantities of plagioclase crystalloblastic mosaics, the barren breccia grades into less brecciated, but plastically deformed Footwall rocks.

ORIGIN OF THE FOOTWALL BRECCIA

Footwall Breccia along the North Range lies within the pyroxene hornfels contact metamorphic zone and has a consistently close contact relationship with the mafic norite-Sublayer of the Sudbury Igneous Complex. Chemical analyses of Footwall Breccia matrix from the Strathcona and Hardy Mines listed in Table 14.4, have been added to the triangular plots of Figure 14.2. It is clear that the breccia matrix is compositionally similar to the more felsic units (analyses 1 to 6 inclusive, Figure 14.2) in the Footwall. The sodium metasomatism noted by Hebil (1978) and Naldrett and Kullerud (1967) in some Footwall Breccia is not recognized in these analyses, and it is inferred that their observations must relate to sodium redistribution rather than metasomatism. The introduction of sulphides has also not been accompanied by recognizable increases in silica content. The abundance of secondary hydrous silicates in the Footwall Breccia, however, would infer that water was available to the system.

The Footwall Breccia is characterized by a poikiloblastic secondary metamorphic mineralogy, in which large, optically continuous grains of "flood"

TABLE 14.4: CHEMICAL ANALYSES OF FOOTWALL BRECCIA.

SAMPLE NUMBER	A	B	C	D	E
Major Oxides ^a					
SiO ₂	60.1	64.8	57.7	56.7	66.1
TiO ₂	0.42	0.46	0.82	0.87	0.38
Al ₂ O ₃	15.5	14.7	15.4	17.1	17.0
Fe ₂ O ₃	—	—	1.82	3.79	1.64
FeO	4.37 ^a	3.64 ^a	5.75	4.00	1.20
MnO	0.03	0.04	0.13	0.10	0.03
MgO	2.30	1.34	4.32	3.25	1.10
CaO	4.40	3.77	5.56	6.39	4.14
Na ₂ O	4.90	5.28	3.45	4.62	5.10
K ₂ O	1.01	1.40	1.50	0.85	1.40
P ₂ O ₅	—	—	0.24	0.35	0.10
CO ₂	—	0.05	0.13	0.10	0.10
S	—	0.21	0.23	0.07	Nil
Total	93.03	95.69	97.05	98.19	98.29
L.O.I. ^b	0.20	0.93 ^a	1.91 ^a	1.23	0.85
Trace elements ^c					
Cr	—	274	175	89	144
Cu	—	—	380	110	16
Ni	100	393	91	28	13
Pb	—	—	35	4	8
Rb	—	—	—	0	10
Sr	—	—	—	630	500
Zn	—	—	95	71	23
Zr	—	—	—	210	80

Notes: a. weight %

b. loss on ignition

c. in ppm

d. total Fe as FeO

e. H₂O +

— not determined

A. Average unmineralized breccia matrix n = 2, Strathcona Mine (Cowan 1968)

B. Average barren breccia matrix n = 8, Strathcona Mine (Greenman 1970)

C. Weakly mineralized grey Footwall Breccia, Hardy Mine

D. Early transitional stage from opx. diorite, Strathcona Mine

E. Early transitional stage from opx. tonalite, Strathcona Mine

quartz enclosing recrystallized plagioclase and areas of granophyric intergrowth, are prevalent. Some large plagioclase laths have developed by epitaxial growth on smaller stubby crystals. Granophyre in the breccia matrix increases in abundance toward the norite contact, and at its maximum development, the rock is essentially a granophyre with strongly digested fragments. Felsic fragments become less identifiable as they merge with the recrystallized matrix, whereas the more refractory anorthositic, mafic, and ultramafic fragments maintain their form despite being hornfelsed.

All evidence favours an *in situ* metamorphic origin for the Footwall Breccias. The temperature regime in the Footwall rocks at the time of the intrusion of Sublayer and associated sulphides has been examined by Naldrett and Kullerud (1967) and Dressler (Chapter 6, this volume). The former authors determined the melting temperature of a typical sample of the matrix

of the Footwall Breccia under hydrothermal conditions. At 850°C and 750 bars water pressure, no melting was observed, but limited melting occurred at 1000 bars at the same temperature. By analogy with the melting curve of the ternary minimum in the quartz-albite-orthoclase system, the authors estimated that melting would occur at 900°C under 500 bars, and at 950°C under 250 bars water pressure. The experimental work of von Platen (1965), however, has indicated that granodioritic rocks were predominantly molten at 800 to 850°C under 2000 bars water pressure and that incipient melting would occur at about 700°. Experimental work by Craig (1966) and quoted by Naldrett and Kullerud (1967), has shown that sulphides + magnetite in the average proportions present in Strathcona ore will start to melt at $1019 \pm 5^\circ\text{C}$, and even assuming high total pressure, the solidus in the dry experiment would not be lowered by as much as $\pm 20^\circ\text{C}$. The authors predict that the sulphide-oxide magma of the Footwall ore must have been introduced at a temperature above 1000°C. These authors, however, failed to recognize that partial melting of the Footwall rocks has occurred.

Figure 14.3 diagrammatically depicts the generalized contact relationship between Sublayer norite, layered Footwall rocks, and the intervening Footwall Breccia as observed in the Onaping-Levack area. Partial melting of felsic components of the Layered Footwall Complex, permitted flowage under pressure

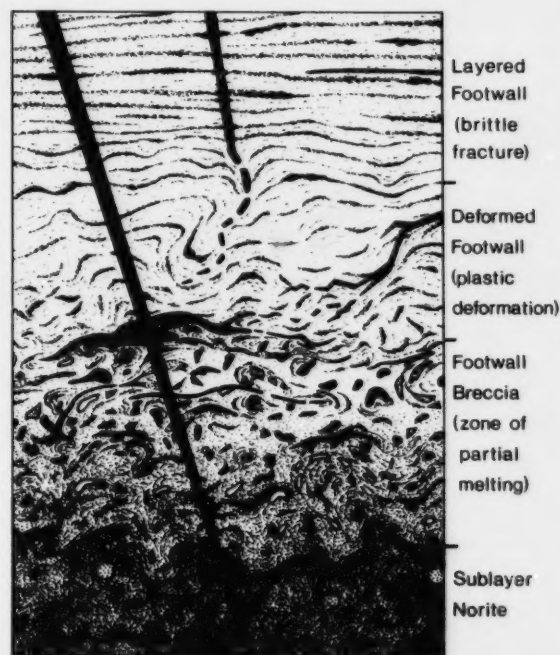


Figure 14.3 Diagrammatic portrayal of generalized contact relationships between Sublayer norite and layered Footwall rocks. Sulphides (black). Not to scale.

resulting in fragmentation of more refractory mafic, ultramafic, and anorthositic layers. Progressively decreasing fragmentation of layers is evident outward from the contact and is replaced by a zone of flow-deformed, contorted layering. This in turn grades outward to recrystallized, but essentially undeformed rocks.

SULPHIDE ORE DEPOSITS

Ore deposit descriptions for the Onaping-Levack area include those for the Hardy Mine (Mitchell and Mutch 1957), the Levack Mine (Souch, Podolsky *et al.* 1969), the McCreedy West Mine (Hoffman *et al.* 1979) and the Strathcona Mine (Naldrett and Kullerud 1967; Cowan 1968; Abel *et al.* 1979; Nikolic 1979; Abel 1981). Sulphide mineralization is categorized on the basis of structural location, host rock, and mineralogy and can therefore be subdivided into the following ore types:

1. disseminated sulphides in mafic norite
2. disseminated, stringers, breccia sulphides, and massive lenses in the Sublayer
3. massive and breccia sulphides at the contact of Sublayer with Footwall Breccia
4. disseminated, breccia, fragmental and massive stringer sulphides in Footwall Breccia
5. massive stringers and lenses of sulphides in Footwall rocks
6. dike-like veins and stringers of massive Cu-rich sulphides in Footwall rocks

Each deposit of the North Range consists of one or more of the listed ore types in a wide range of structural and lithological settings. These will be discussed with reference to the accompanying plans and sections.

Structural and Lithologic Setting

Plans 1, 2, and 3 (Chart B, back pocket) illustrate projected geology at the 1475-, 2500-, and 3600-foot levels, respectively. Shaft locations and section lines are suitable reference features for comparing the 3 plans.

The part of the belt west of the Fecunis Lake Fault is host to the Hardy, Boundary, Onaping, Craig, McCreedy West, and Levack ore deposits. Except for minor undulations, due to variable thicknesses of Sublayer and Footwall Breccia units, the contact is relatively straight. A substantial thickening of these units is apparent near the Fecunis Lake Fault at the 1475 level in the vicinity of the Levack orebodies and on the 3600 level, where they host the deeper Craig orebodies.

On the eastern side of the fault, the belt contains the Big Levack, Longvack, Coleman, Strathcona,

Fraser, McCreedy East, North, Fecunis, and part of the Levack ore deposits. The main feature of this area is a prominent outward bulge of the norite-Footwall contact, termed the Strathcona Embayment (Cowan 1968). The Embayment is characterized by substantial thickening of the mafic norite and Sublayer units accompanied by thicker zones of Footwall Breccia. From its surface exposure on the Longvack property, the Embayment plunges 23° southwest to the vicinity of the Fraser and McCreedy East ore zones. From there, the plunge maintains an essentially horizontal attitude across to the vicinity of the Fecunis Lake Fault. At the Coleman Mine, the Embayment is 600 m in width, with the mafic norite and Sublayer attaining a thickness of up to 350 m.

Two strike faults are conspicuous features on the 3 level plans. The Number 1 Hanging wall Fault can be traced from the Onaping Mine to the eastern part of Longvack Mine, with an average strike of N55E and an average dip of 40° southeast. It is confined to norite for the most part, but locally extends into Footwall rocks. The structure is known to have vertical continuity for 1500 m and is cut by the later Fecunis Lake and Bob's Lake cross Faults. The Number 2 Hanging wall Fault can be traced for 1.5 km in the Fraser-Strathcona Mines area, where it dips 40° to 50° southeast. Of local importance in the Fraser Mine area is the Fraser Number 2 Fault, which parallels the Bob's Lake Fault and dips 40° northeast.

The structural and lithologic setting of the orebodies is more readily apparent on cross-sections. Figure 14.4 (Section A) illustrates a cross-section through the Onaping area at the western end of the belt. Lower Zone felsic norite is intermittently underlain by varying thicknesses of mafic norite-Sublayer and Footwall Breccia. The McCreedy West deposit, formerly termed Levack West, at the elevation of Plan 1 has been described briefly by Hoffman *et al.* (1979). It

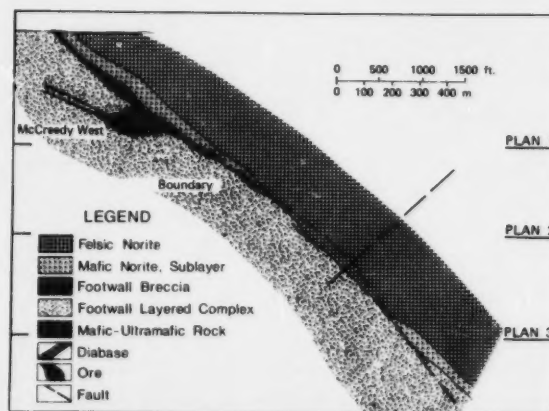


Figure 14.4. Geological Section A (looking east), Onaping-Levack area.

consists of a Main ore zone of mineralized Footwall Breccia ("granite breccia") that occupies an embayment in the Footwall. Massive, breccia, and disseminated sulphides are present, with the latter having a possible fragmental texture. Main ore zone sulphides grade into Footwall ore zone sulphides, which consist of massive sulphide veins in Footwall rocks and associated bodies of Sudbury Breccia. The veins vary in width from 1 mm to about 2 m and consist of massive chalcopyrite, pyrrhotite, and pentlandite. Copper-rich stringers extend outward from the Footwall ore zone to greater depths beneath the contact. Mineralization in Footwall rocks forms part of the Boundary and Onaping Ore deposits immediately down-dip from the McCree West deposit, at about the elevation of Plan 2. The ore zones occur close to the felsic norite, where mafic norite and Footwall Breccia pinch out, and felsic norite is in direct contact with Footwall rocks.

On Figure 14.5 (Section B), which illustrates the general setting of the Craig ore deposits, felsic norite is in relatively smooth contact with mafic norite and Sublayer. Variable thicknesses of these units, together with irregular zones of Footwall Breccia combine to form an irregular contact with Footwall rocks. The largest parts of the Craig deposits occur in Footwall Breccia as massive stringers and breccia sulphides and have a general alignment parallel to the norite contact. Smaller zones of mineralization are present locally as stringer sulphide in Sudbury Breccia and as disseminated to massive sulphides in Sublayer norite. Disrupted units of mafic to ultramafic rocks occur in the Footwall Complex in this section.

The varying widths of mafic norite and Sublayer shown on the 3 Plans at Section C are illustrated in Fig-

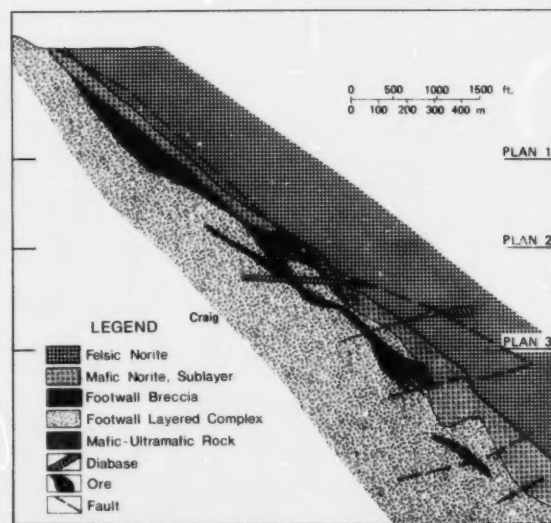


Figure 14.5. Geological Section B (looking east), Onaping-Levack area.

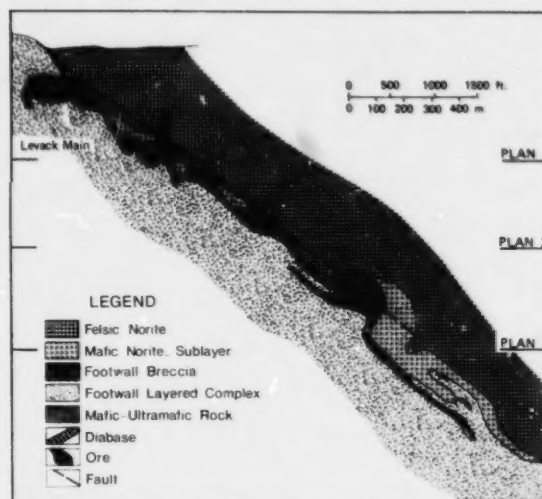


Figure 14.6. Geological Section C (looking east), Onaping-Levack area.

ure 14.6. Footwall Breccia underlies mafic norite and Sublayer from the surface to below the 3600 level of Plan 3. Although not defined in detail, this section shows an apparent intruding lobe of Footwall Breccia into the overlying mafic and felsic norites. The irregularly-distributed mineralization of the Levack Main deposit occurs in Footwall Breccia and as stringers in Footwall rocks. Relatively minor sulphide mineralization occurs in Sublayer norite.

Figures 14.7 and 14.8 (Section D and E) illustrate the complexities produced by the west-dipping Fecunis Lake Fault. The apparent thickening of mafic norite-Sublayer and Footwall Breccia evident on Plan 1 at the 1475 level is shown on Section C (Figure 14.6) to result from the flattening of the norite contact and the development of Footwall Breccia in an embayment structure. This feature appears to control the location of the Levack Number 2 ore zone. The large Levack Number 3 deposit is situated in Footwall rocks between the embayment and Fecunis Lake Fault.

On Figure 14.8 (Section E), a large nose-like embayment structure of Sublayer and Footwall Breccia beneath the Fecunis Lake Fault is host to the Levack Number 4 and Fecunis Lake ore deposits. Souch, Podolsky *et al.* (1969) described this complex feature in the following way, from a generalized section through the area. Mafic norite overlain by felsic norite dips southward across the head of the embayment following the regional trend of the contact. The underlying Sublayer consists of sulphide- and inclusion-bearing basic norite, sulphide-bearing Footwall Breccia, and inclusion massive sulphide. Sulphides in the basic norite occur as sparsely distributed patches, but in

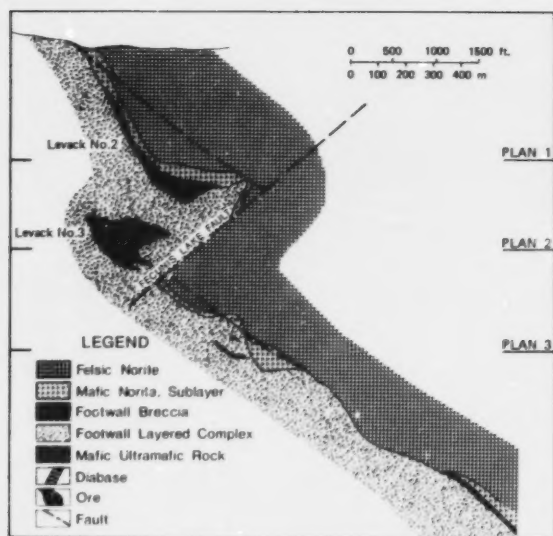


Figure 14.7. Geological Section D (looking east), Onaping-Levack area.

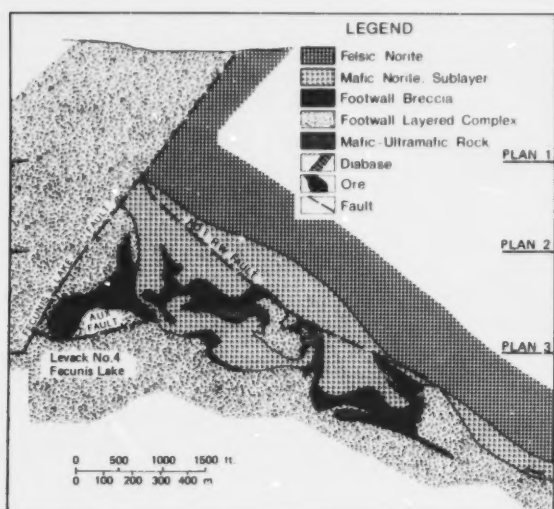


Figure 14.8. Geological Section E (looking east), Onaping-Levack area.

some inclusion-rich areas have been sufficiently concentrated to make ore. Sulphides in Footwall Breccia occur as blebs, that locally coalesce into pods and stringers and as a whole account for 2/3 of the ore. Inclusions of massive sulphide form the tip of the nose and comprise the remaining 1/3 of the ore. It contains scattered angular inclusions of Footwall rock and apparent segregations of leuconorite rich in alkali feldspar.

Remaining sections to the east display increasing irregularity in the felsic norite-mafic norite contact of the Lower Zone, accompanied by the development of the distinctive Strathcona Embayment Structure. In

Figure 14.9, (Section F), mafic norite and Sublayer rocks with an irregular sheath of Footwall Breccia occupy a downward projecting, relatively narrow embayment feature in the Footwall. At the apex of this structure, disseminated sulphides in Sublayer norite constitute the North Depth deposit. It is associated with a number of smaller zones in Footwall Breccia, distributed irregularly around the embayment. Of interest in this section, are the wide cross-cutting diabase dikes and a Footwall layer of mafic-ultramafic rocks.

In Figure 14.10 (Section G), local thickening of mafic norite and Sublayer rocks, together with large irregular areas of Footwall Breccia outline a much broader aspect of the embayment. Footwall Breccia surrounds and invades large blocks of Footwall rock in what can be described as a megabreccia. Lobes of Footwall Breccia also appear to penetrate upward into overlying mafic norite. The large McCreedy East and Fraser ore zones occur as blebs, veins, stringers, and massive breccia sulphides in both Footwall Breccia and Footwall rocks. The deposit as a whole is located close to the outermost limit of Footwall brecciation and varies in dip from vertical at its upper extremity to near horizontal at the lower end. This variation in structural attitude closely parallels the Sublayer-Footwall Breccia contact. Additional mineralized zones occur as disseminated patchy sulphides in Sublayer norite and as veins in Footwall Breccia.

The mafic-ultramafic unit of the Footwall, which became prominent in the prior Section, exhibits extensive lateral continuity in Section G. The Fraser Epidote zone of mineralization consists of disseminated and stringer nickel-rich sulphides hosted by this unit.

The southwest plunge of the Strathcona Embayment is evident from Figures 14.11 and 14.12 (Sections H and I), where it occurs at successively shallower elevations. On Figure 14.11 (Section H), the Embayment contains a thick unit of mafic Sublayer rocks and a partial envelope of Footwall Breccia. Parts of the Strathcona, McCreedy East, and Fraser deposits are located in zones of Footwall Breccia. A relatively small proportion of the total sulphides occurs as disseminated patches in the Sublayer. Section H also illustrates the location of some of the copper-rich veins of the Strathcona Deep Copper Zone in Footwall rocks, about 550 m beneath the contact.

In Figure 14.12 (Section I), the Strathcona Embayment attains its greatest thickness of mafic norite-Sublayer and exhibits wide lateral zones, both up and downdip of the Footwall Breccia. A narrower band of Footwall Breccia surrounding the embayment hosts the Upper Coleman and Strathcona Main zone deposits. Irregular, discontinuous, disseminated ore zones occur in Sublayer units at the Strathcona Mine and in addition, sheet-like lenses of massive and breccia sulphides constituting the Strathcona Deep Zone oc-

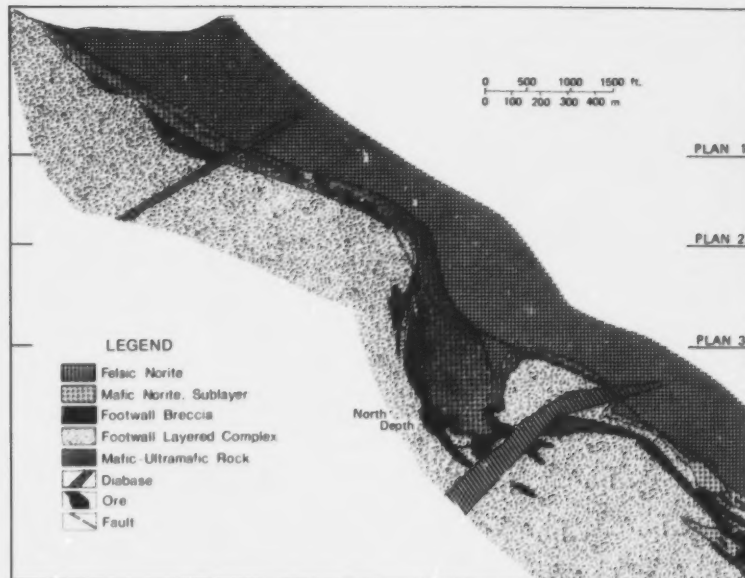


Figure 14.9. Geological Section G (looking east), Onaping-Levack area.

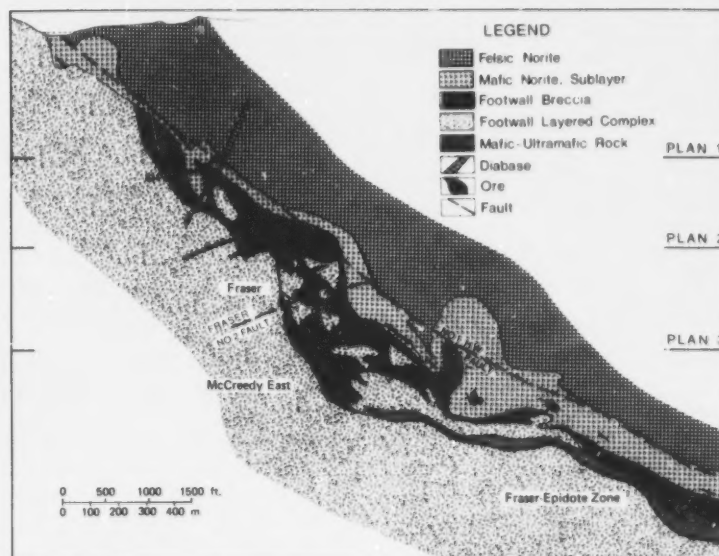


Figure 14.10. Geological Section F (looking east), Onaping-Levack area.

cur in Footwall rocks up to 200 m beneath the contact. Downdip from the Strathcona Main Zone, the Lower Coleman deposits occur in an extensive zone of Footwall Breccia. Strathcona Copper Zone stringers in the Footwall are also indicated on Figure 14.12, showing an apparent dip towards the Deep Zone deposit.

From this brief review of the structural and lithological setting of the Onaping-Levack ore deposits, some general observations can be made:

1. Ore deposits are spatially related to embayment structures, which represent local thickenings of mafic norite and mineralized Sublayer units projecting downward into Footwall rocks. Embayments are usually reflected by the overlying felsic norite, but in some instances, the latter appears to overlie the top of the structures in a relatively straight and smooth contact.

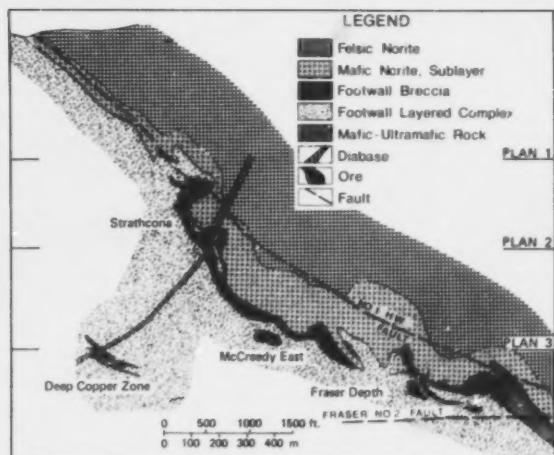


Figure 14.11. Geological Section H (looking east), Onaping-Levack area.

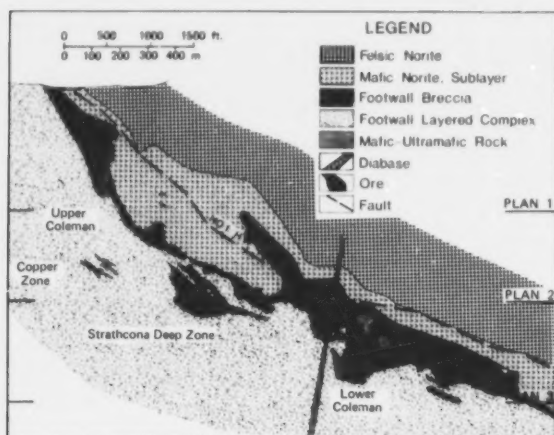


Figure 14.12. Geological Section I (looking east), Onaping-Levack area.

2. Footwall Breccia is restricted to a zone adjacent to, or at least close to the contact of the Sudbury Igneous Complex. It reaches its greatest development in Footwall rocks coincident with embayment structures. Lobes of Footwall Breccia penetrate the overlying norite in a number of places, implying mobility of this material, penecontemporaneously with its formation. An *in situ* origin by partial melting of leucocratic layers in the Footwall Complex accompanied by differential movement and subsequent fracturing and breakup of refractory layers is considered the most probable sequence of events.
3. Footwall Breccia is quantitatively the most important host rock for sulphide deposits. Ore types include a wide range of textural varieties, ranging from disseminated, blebby, breccia sulphides having a variety of inclusions and massive sulphide stringers.

4. Ore zones in the Footwall, beyond the limit of Footwall Breccia, are composed of lenses and veins of massive sulphide separated from each other by barren Footwall rock. The most distant from the contact are the massive, fracture-filling sulphides of the copper zones.

Sulphide Mineralogy

In terms of sulphide mineralogy, the ore types described in the prior section can be readily grouped into 3 distinct associations:

1. nickel-copper sulphides comprising the bulk of the economic ore in the North Range, hosted by Sublayer, Footwall Breccia, and adjacent Footwall rocks
2. copper-rich sulphide vein deposits hosted by Footwall rocks
3. nickel-rich disseminated sulphides associated with mafic to ultramafic rocks in the Footwall

The major constituents in Group 1 deposits are pyrrhotite, pentlandite, and chalcopyrite together with minor amounts of pyrite, magnetite, and ilmenite. Two pyrrhotite types are present in the ore at the Strathcona Mine. Vaughan *et al.* (1971) described the first as monoclinic, of composition $(\text{Fe}, \text{Ni})_{7.8}\text{S}_8$ containing 0.35 to 0.50% Ni and the second as hexagonal, of composition $(\text{Fe}, \text{Ni})_{9.1}\text{S}_{10}$ with 0.68 to 1.01% Ni. The distribution of the pyrrhotite types, based on a determinative method developed by Graham (1969) is documented by Cowan (1968). Hexagonal pyrrhotite forms a small percentage of the total pyrrhotite in the Strathcona Hanging wall Zone, but increases toward the basal contact of the Sublayer. Similarly, there is an increase toward the base of the Deep Zone in Footwall rocks, where the proportion of hexagonal pyrrhotite is >40%. As the separation of these pyrrhotite phases occurred below 300°C (Arnold 1969; Taylor 1970), their varying proportions reflect differences in initial bulk pyrrhotite composition. This in turn, implies metal zonation and redistribution.

Pentlandite is the dominant nickel-bearing sulphide in the area, occurring as fine exsolution lamellae oriented parallel to the basal parting of pyrrhotite and as rims or blocky grains filling interstices between pyrrhotite crystals. The nickel content of pentlandite ranges from 34.2 to 36.2% and the cobalt content is generally about 1%.

Chalcopyrite is ubiquitous in North Range ores and at the Strathcona Mine is more abundant in the Main and Deep Zones than it is in the Hanging wall Zone. In copper-rich areas at the base of the Deep Zone ore bodies, chalcopyrite occurs as masses up to several

cm in diameter or as discrete cross-cutting veins. Marginal parts of the Levack Number 4 and McCreedy West deposits are also copper-enriched, and stringers of massive chalcopyrite extend outward from the main ore zones into adjacent Footwall rocks.

Pyrite occurs throughout the ores with a wide variation in distribution and abundance. It is common as euhedral grains around xenoliths. Magnetite is also present as equant grains within the sulphides and usually contains some exsolved ilmenite lamellae.

The second association of sulphides is that of the copper-rich vein deposits hosted by Footwall rocks. Abel *et al.* (1979) have described 2 veins of the Strathcona Copper Zone which consist of chalcopyrite, cubanite, pyrrhotite, and pentlandite, in that order of abundance. Chalcopyrite and cubanite form the bulk of the assemblage with an average ratio of 3.7:1. Accessory minerals include sphalerite, nickeliferous mackinawite, and primary and secondary magnetite. Pentlandite constitutes an estimated 1.5% of the total assemblage, occurring as large blocky crystals up to 10 cm across. These are invariably replaced to some extent by chalcopyrite, cubanite, and pyrrhotite along cleavage planes and shrinkage cracks. Pentlandite also occurs as massive selvages to some chalcopyrite veins, and in some narrow stringer constitutes the entire infilling sulphide assemblage. Although not abundant, millerite and bornite occur sporadically in Copper Zone veins, as clusters of coarse crystals and massive patches, respectively.

Of interest is the occurrence of talnakhite, associated with cubanite and pentlandite in diamond-drill hole intersections of the Deep Copper Zone at the Strathcona Mine. Talnakhite, first recognized by Cabri (1967) and documented by Cabri and Harris (1971) from the copper-nickel ores at Norilsk, occurs with cubanite as coarse-grained, intimately intergrown masses. Cubanite also forms abundant lamellae in the talnakhite, oriented along crystallographic planes and is occasionally continuous with marginal masses of cubanite. Talnakhite is metastable, quickly tarnishing in air to various hues of orange, brown, and red. Along fractures it develops a deep purple iridescent colour. Small pits and fractures in talnakhite and pentlandite are filled with lawrencite (FeCl_2), which is hygroscopic and readily oxidizes to akaganéite (βFeOOH). Lawrencite has been identified in volcanic sublimates and in some meteorites (Winchell and Winchell 1951), while akaganéite, first described from the oxidation zone at Akagané Mine, Japan (Mackay 1962), has also been recognized in Apollo 16 lunar samples (Taylor, Mao, and Bell 1973, 1974). The presence of these minerals in the Strathcona Deep Copper Zone is noted here, however, with no implied genesis for the Sudbury Structure. The full compliment of minerals so far identified in Copper Zone ores are listed in Table 14.5.

TABLE 14.5: MINERALS IDENTIFIED IN STRATHCONA COPPER ZONES.

Acanthite	Ag_2S
Akaganéite	βFeOOH
Altaite	PbTe
Argentine Pentlandite	$(\text{Fe}, \text{Ni})_9\text{Ag S}_8$
Bornite	$\text{Cu}_5\text{Fe S}_4$
Chalcocite	Cu_2S
Chalcopyrite	Cu Fe S_2
Cubanite	$\text{Cu Fe}_2\text{S}_3$
Dyscrasite	Ag_3Sb
Electrum	Ag Au
Empressite	Ag Te
Froodite	Pd Bi_2
Galena	Pb S
Galencbismutite	$\text{Pb Bi}_2\text{S}_4$
Hauchecornite	$\text{Ni}_3(\text{Bi}, \text{Sb}, \text{Te})_2\text{S}_8$
Hawleyite	CdS
Hessite	Ag_2Te
Ilmenite	Fe Ti O_3
Lawrencite	FeCl_2
Mackinawite	$(\text{Cu}, \text{Ni})\text{Fe S}_{1.1}$
Magnetite	Fe_3O_4
Millerite	NiS
Moncheite	$(\text{Pt}, \text{Pd})(\text{Bi}, \text{Te})_2$
Native bismuth	Bi
Native gold	Au
Native silver	Ag
Niggliite	$(\text{Pt}, \text{Sn})(\text{Bi}, \text{Te})$
Parkerite	$\text{Ni}_3\text{Bi}_2\text{S}_2$
Pentlandite	$(\text{Fe}, \text{Ni})_9\text{S}_8$
Pyrite	Fe S_2
Pyrrhotite	Fe_{1-x}S
Sperryite	Pt As_2
Sphalerite	ZnS
Stannopalladinite	Pd_2Sn_2
Stibnite	Sb_2S_3
Talnakhite	$\text{Cu}_{18}(\text{Fe}, \text{Ni})_{16}\text{S}_{32}$
Tellurobismutite	Bi_2Te_2
Tetradymite	$\text{Bi}_2\text{Te}_2\text{S}$
Violarite	$\text{Fe Ni}_2\text{S}_4$

The third sulphide association referred to previously is the so-called Epidote Zone at Fraser Mine. At present, little is known of the extent of this mineralization, but it is not regarded as volumetrically significant. Pentlandite, pyrrhotite, and chalcopyrite are the sulphides present, having an unusually high pentlandite to pyrrhotite ratio. The sulphides form fine-grained disseminations in an epidote-tremolite $\pm$ quartz-carbonate assemblage, believed to have resulted from Ca and Mg migration during thermal recrystallization of spacially associated mafic to ultramafic rocks within the Footwall Complex.

In addition to the sulphide associations described, disseminated chalcopyrite, pyrrhotite, and occasionally bornite are distributed in some intermediate and mafic units of the Footwall Archean layered complex in the general vicinity of the Copper Zones. This mineralization appears to be lithologically controlled and is thought to be a primary magmatic phase of the Complex. No economic concentrations of primary Footwall sulphides are known, however, and additional work will be required to document the silicate-sulphide relationships and composition of the host lithologies.

Copper and Nickel Distribution

Except for the Strathcona Deposit, little detailed information is available on the distribution of Cu and Ni in the sulphides of the Onaping-Levack area. The Strathcona Deposit consists of the Hanging wall Zone in the Sublayer, the Main Zone in Footwall Breccia, and the Deep Zone in rocks of the Footwall Complex. Calculating percentage values for nickel in sulphides from 3000 analyses of Cu, Ni, and S, Cowan (1968) detected a pronounced zonation in the distribution of nickel. The content in Hanging wall sulphides is low and relatively constant at between 2.5 to 3.0%. In contrast, the Main Zone ore is strongly zoned with minimum values of 3.0% adjacent to the norite, to a maximum of 5.0% in places close to the Footwall contact. Contoured values of % Ni in sulphide in the Main Zone, closely follow the trend of the norite contact, and individual ore lenses may be transected by several contours, indicating that they do have a single characteristic value. Within the Deep Zone, Ni in sulphide values are less variable, but do indicate lower values of 4.0 to 4.5 in the central part, with somewhat higher values above and below. Values increase to a maximum of 6.0 at the base of the Deep Zone. More detailed investigation of nickel distribution at Strathcona by Nikolic (1979) indicates that the Deep Zone is concentrically zoned with higher values in marginal areas surrounding lower values in the core or central part. Even though the Main Zone and Deep Zone show increasing values of Ni in sulphides away from the basal contact of the norite, the Deep Zone ore is zoned independently and the pattern as a whole does not increase progressively outward from the Main Zone through the Deep Zone.

The Strathcona study of Cowan (1968) also indicated a similar trend of copper enrichment away from the contact. The distribution of Cu is generally more variable than that of Ni, but significant increases of Cu:Ni ratios from the Hanging wall to the Footwall of the Main Zone and towards the base of the Deep Zone are an obvious feature of the deposit. Stringers of massive chalcopyrite at the base of the Deep Zone are common. The veins of the Strathcona Copper and Deep Copper Zones appear to represent an outward extension of this zoning pattern. In contrast, Co content in the Strathcona ores decreases outward from the contact. Ni/Co ratios in Hanging wall ores average 15.7, Main Zone ore 21.6, and for Deep Zone sulphides, 43.5.

On a more regional scale, the North Range ore deposits have significant variations in Cu, Ni, and Co content and % Ni in sulphide values. When bulk compositions of individual ore deposits are plotted in terms of Cu-Ni+Co-S, the 3 distinct sulphide associations described previously, are readily apparent (Figure 14.13). Calculated % Ni in sulphides and Cu/Cu + Ni

values for some deposits are plotted on a diagrammatic vertical longitudinal projection, extending from the Hardy to the Longvack South deposits (Figure 14.14). Each value represents a calculation based on bulk composition of individual ore zones, with the dots indicating the approximate central point of the appropriate deposit. It should be noted that these locations, while indicating true vertical depth below surface, do not relate to positioning with respect to the contact. Nevertheless, there is a suggested trend of increasing values for % Ni in sulphides and decreasing Cu/Cu + Ni ratios with depth. This is especially evident for the ore deposits at the more easterly and westerly parts of the mineralized belt.

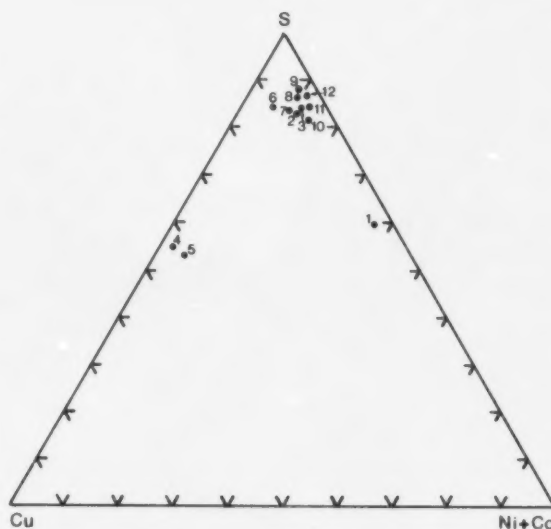


Figure 14.13. Plot of bulk compositions in Cu-Ni + Co-S system for some North Range ore deposits. (1. Fraser Epidote Zone; 2. Fraser Main; 3. Fraser Depth; 4. Strathcona Copper Zone; 5. Strathcona Deep Copper Zone; 6. Strathcona Copper Zone-pyrrhotite veins; 7. Strathcona Deep Zone; 8. Strathcona Main; 9. Strathcona Main; 10. Craig; 11. Onaping 2; 12. Onaping 3).

Distribution of Platinum Group Elements, Gold, and Silver

Published data on the platinum group elements (PGE's), Au, and Ag for the area are sparse and incomplete. Cabri and Laflamme (1976) pointed out that, whereas, arsenides and sulpharsenides containing PGE's are common on the South Range, they are absent or very rare on the North Range. PGE's in the latter only exist in distinct platinum group minerals (PGM's) within the common sulphides. Several workers (Hoffman *et al.* 1979; Naldrett 1981; Naldrett *et al.* 1982) have found that PGE distribution varies predictably from the Hanging wall of the sulphide environment to the Footwall. Rh, Ru, Ir, and Os are

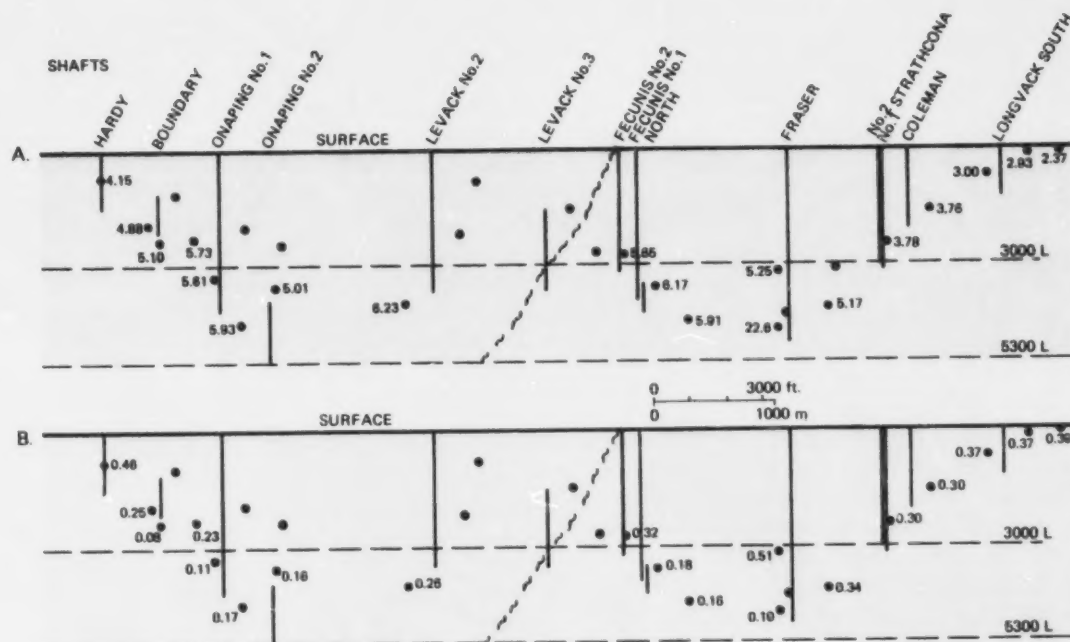


Figure 14.14. Diagrammatic vertical longitudinal section of the Onaping-Levack area. Dots represent approximate central locations of individual ore zones. A. Percent nickel in sulphides. B. Ratios of Cu/(Cu + Ni).

TABLE 14.6: CONCENTRATION OF METALS IN MASSIVE SULPHIDE FROM COPPER-ENRICHED FOOTWALL ZONES.

	Cu (Wt.%)	Ni (Wt.%)	Co (Wt.%)	Pt (ppb)	Pd (ppb)	Rh (ppb)	Ru (ppb)	Ir (ppb)	Au (ppb)	Ag (ppb)
McCreedy West ¹	27.59	5.52	—	11 434	13 670	< 44	< 130	< 44	8211	254 000
Coleman ¹	29.05	1.75	—	2403	3713	< 17	51	< 17	2678	105 258
Strathcona ²	29.60	0.39	0.02	2551	890	—	—	—	189	55 240
Strathcona ³	24.67	1.72	0.05	4910	6970	—	—	—	4880	118 320
Deep Copper										

¹ Values calculated from assays of a representative diamond-drill hole composite sample

² Average values calculated from assays of selected samples (n = 32)

³ Values averaged from diamond-drill hole composite samples (n = 21)

enriched in the Hanging wall sulphides (as is Co), and Pt, Pd, Au, and Cu, are enriched in Footwall environment sulphides. This trend would seem to be consistent from the western end (McCreedy West deposit), through the central part (Levack deposit), to the eastern end (Strathcona-Coleman deposit). Silver concentrations in typical orebodies, excluding the Footwall copper veins, appear to be directly and uniformly dependent upon copper concentrations. However, within the chalcopyrite-rich Footwall zones, there is significant, but variable enrichment of Ag, to the degree that native Ag has been observed in both the Strathcona and McCreedy West copper zones.

At McCreedy West, chalcopyrite-rich stringer ore extending well into the Footwall environment represents a relatively small, but significant part of the total

sulphide content of the mine. Hoffman *et al.* (1979) considered this material "atypical" and excluded its assay results from their mine average, stating that it was "not believed to be significant volumetrically". Sampling of the copper zone was not as extensive or as representative as the sampling from the "main" zone. More representative values for the McCreedy West copper zone are given in Table 14.6. Incorporation of these values into Hoffman's McCreedy West Mine average, necessitates a weighting based on the sulphide content of the original total deposit prior to any mining. It is estimated that the Cu-rich Footwall environment sulphides represented some 13% of the total sulphides in the deposit. The weighted mine averages are indicated in Table 14.7 and are compared to the values from Hoffman *et al.* (1979), which exclude the Footwall zone.

TABLE 14.7: CONCENTRATION OF THE PGE'S AND Au IN MASSIVE SULPHIDE FOR TOTAL MCCREEDY WEST DEPOSIT (ppb).

	Pt	Pd	Rh	Ru	Ir	Au
This Paper	2490	2867	168	69	47	1198
Hoffman <i>et al.</i> (1979)	1154	1253	186	60	47	50

The revised values are considerably higher for Pt, Pd, and Au than those calculated by Hoffman *et al.* (1979) and later were quoted by Naldrett (1981). In fact, they compare very favourably with the concentrations reported by Hoffman *et al.* (1979) for the Little Stobie Number 2 orebody on the South Range.

Early work on the Strathcona Copper Zone by Abel *et al.* (1979) suggested a low level of PGE's in the sulphides. This was supported by the analysis of a single sample from the zone published by Naldrett (1981), and later quoted by Naldrett *et al.* (1982), which showed concentrations of PGE's and Au at levels considerably below those of the Strathcona Deep Zone. More extensive sampling of the zone, concurrent with mining operations, shows that in fact it has an identical concentration of Pt, but lower levels of Pd, Au, and Ag than the contiguous Coleman zone (Table 14.6). The Coleman zone represents the up-dip, more distal part of the Strathcona Copper Zone, and they can be logically considered a single mineralized unit. Veins of the Strathcona Deep Copper Zone, located deep in the Footwall rocks (Figure 14.11, Section H), contain approximately twice the content of Pt, Pd, and Au to that of the Coleman values, and about the same Ag content.

The copper-rich stringers at the McCreedy West deposit are contiguous with the main ore zone, extending out into Footwall rocks to form the Footwall ore zone. As such, they are not strictly geologically analogous to the Strathcona-Coleman and Strathcona Deep Copper Zones, which occur in the Footwall with no detected physical connection to the Strathcona Main or Deep Zone ore bodies. Even though the Strathcona-Coleman and Strathcona Deep Copper Zones do not show the dramatic increase in PGE concentration of copper-rich stringers over Footwall ore at McCreedy West, they can be considered to be chemically analogous, in that they exhibit a PGE, Au, and Ag enrichment, which is the culmination of progressively increasing content outward from the Hanging wall, Main, and Deep Zone ore bodies.

DISCUSSION OF SULPHIDE AND ORE ZONE GENESIS

From the observations and studies of Souch, Podolsky *et al.* (1969), Naldrett and Kullerud (1967), and Craig and Kullerud (1969), it is presently generally accepted

that the ores were introduced as a sulphide-rich liquid carried by xenolith-bearing magma. Intrusions of this magma, marginal to the Main Mass of the Sudbury Igneous Complex, formed embayment structures in the underlying Footwall rocks. It is with these features that the principal North Range ore deposits are associated.

A pronounced thermal metamorphic aureole has been described in the layered Footwall rocks of the Onaping-Levack area. At the norite contact, the grade of metamorphism reaches the pyroxene hornfels facies. Within this high grade contact metamorphic zone, favourable conditions induced partial melting of the leucocratic quartz-rich parts of the layered complex. Concurrent movement and mobilization of this material caused an autobrecciation of more refractory mafic, ultramafic, and anorthositic layers. Geological sections through the North Range demonstrate that maximum development of Footwall Breccia is coincident with embayment structures, where Sublayer intrusions are thickest and where temperature conditions would presumably be greatest. The contact between ore-bearing Sublayer and Footwall Breccia is irregular, gradational, and obscure, due in part to intermixing and sulphide introduction.

Xenolith-bearing Sublayer norite contains a sufficiently high percentage of disseminated, blebby, and stringer sulphides to constitute ore in some mines. Outward from this magmatic source rock, ore zones in Footwall Breccia exhibit features consistent with the introduction of sulphides during breccia formation. Sulphides are either diffuse and patchy in distribution, or occur as irregular massive lenses containing innumerable fragments of Footwall rocks, which include anorthositic, mafic, and ultramafic varieties. Rare sulphide fragments have been recognized in some Footwall ores. Some contain mafic silicate minerals and may have originated as disrupted fragments of mineralized Sublayer. Massive sulphide fragments could possibly have resulted from repeated or continued brecciation of sulphide veinlets after initial introduction and crystallization. Megascopic sulphide textures in Footwall Breccia ores are dominated by evidence of mobilization. Sulphide bands appear to flow around included rock fragments and more massive zones are distinctly banded.

Beyond the limit of partial melting and plastic deformation, Footwall rocks reacted to stress by brittle fracture. In this environment, the massive ore of the Strathcona Deep Zone occurs as arcuate, flat-lying, *en echelon* bands, separated from each other by barren Footwall rocks (Cowan 1968). Subangular fragments of Footwall up to 7 m in diameter are contained in, and veined by massive sulphide stringers. Contacts of ore with the host rock are sharp, and there is no evidence of alteration or silicate melting.

Deeper in the Footwall environment, Copper Zone veins and stringers fill sharp-walled fractures.

Abel (1981) has shown that the strike and dip of individual veins in the Strathcona Copper Zone system coincide with the directions that would result if a compressive stress acting normal to the Footwall of the Sudbury Igneous Complex produced conjugate sets of shears. It is evident that copper veins occupy dilatant fractures. Minor lateral movement of the walls to some veins has been observed where they transect veinlets of Sudbury Breccia. However, the structural complexities of the Footwall have not all been analyzed or resolved. Veins of the Deep Copper Zone differ in attitude to those described for the Strathcona Copper Zone, and so, further research remains to be done.

Phase relations in the Cu-Fe-Ni-S system (Craig and Kullerud 1969; Kullerud *et al.* 1969) and the studies of Strathcona sulphide assemblages (Naldrett and Kullerud 1967) indicate that crystallization of monosulphide solid solution (Mss) from an immiscible sulphide melt would begin at approximately 1125°C. These studies also show that pyrrhotite would be joined by magnetite at about 1055°C. As temperature decreases, exsolution from Mss occurs with pyrite exsolving below 700°C, chalcopyrite below 450°C, and pentlandite below 300°C. Copper solubility in iron-rich Mss is approximately 5% at 900°C decreasing with falling temperature to about 1% at 500°C (Kullerud *et al.* 1969). Copper-rich liquid coexisting with Mss can occur down to a temperature of 850°C and so at magmatic temperatures, precipitation of chalcopyrite directly from this liquid is also possible.

Contributions to the study of metal zonation and distribution in the ore deposits of the North Range include the work of Naldrett and Kullerud (1967), Cowan (1968), Keays and Crockett (1970), Chyi and Crockett (1976), Hoffman *et al.* (1979), and Naldrett *et al.* (1982). In the Strathcona and McCreedy West deposits which have been studied in most detail, there is a pronounced zonation of metals. Cu, Ni, Pt, Pd, Ag, and Au increase in the ores away from the contact into the Footwall, whereas Co, Rh, Ru, Ir, and Os show the reverse trend. We concur with the conclusion of Naldrett *et al.* (1982), that the zoning is the consequence of the fractionation of a sulphide melt primarily due to the crystallization of Mss, with the residual liquid being expelled progressively into the Footwall.

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CHAPTER 15

Ore Deposits of the Copper Cliff Offset

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ABSTRACT

The Copper Cliff Offset begins as a funnel-shaped embayment extending south into the Footwall from the Sudbury Igneous Complex for approximately 2.5 km and then rapidly thins and becomes a steeply dipping dike which averages approximately 40 m in width and extends a further 7 km into the Footwall. Quartz diorite, which is the principal phase of the Offset Sublayer, contains several important copper-nickel sulphide ore deposits.

The quartz diorite normally contains < 0.1% sulphide by weight and has an average copper plus nickel content of 200 ppm. Sulphide concentrations are associated with zones of inclusion-bearing quartz diorite, generally found in the central parts of the dike that probably result from flowage differentiation. The economic sulphide concentrations form inclusion-rich mineralized zones within the quartz diorite dike associated with constrictions in the dike. There are 2 principal ore deposit types.

Deposits typified by the 120 orebody are located in an inclusion-rich zone within the centre of the dike. The sulphides occur as disseminated blebs in the quartz diorite matrix; the sulphide content increases both toward the centre of the zone and down-dip. The sulphides at depth and the weakly mineralized fringe areas are enriched in both copper and precious metals.

Deposits typified by the 810 orebody are located in an inclusion-rich zone along the east contact of the dike. As in the 120 type, sulphides occur as disseminated blebs in the quartz diorite matrix; the sulphide content increases toward the east contact of the dike and down-dip. Chalcopyrite and precious metal contents increase in stringer-type sulphide crosscutting weakly mineralized quartz diorite at depth and in low grade segments along the western parts of the ore zone.

Zoning in ore compositions, as indicated by an increase in chalcopyrite content with increasing distances from the discontinuities in the dike, is interpreted to reflect fractional crystallization of a sulphide melt. The 810 type orebodies are enriched in Cu, Ni, Pt, Pd, and Ag, but are depleted in Co, Rh, Ru, and Ir, compared to the 120 type orebodies. Enrichment of phases with lower crystallization temperatures and differences in the zoning trends appear to result from differences in the attitude of the dike hosting the 810 and 120 type orebodies. The flatter dip of the dike containing the 810 orebodies permitted more efficient gravitational separation of the early formed nickel-rich monosulphide phase and the formation of a copper-rich residual liquid.

INTRODUCTION

The Copper Cliff Offset is a dike of quartz diorite which extends south from the outer margin of the Sud-

bury Igneous Complex to faults associated with the Murray Fault in Broder Township (Figure 15.1). A distal part of the Offset extends an additional 10 km south of the Murray Fault and is described by Grant and Bite (Chapter 12, this volume).

Prospectors found gossans along the dike in 1884, a year after the initial discovery of ore in the Sudbury District was made in a railway cut at what later became known as the Murray Mine.

The Copper Cliff Mine (Figure 15.1) was brought into production by the Canadian Copper Company in 1886. It was the first underground mine in the district. As the name suggests, the ore was mined for its copper content; the fact that the ore also contained nickel was discovered during the smelting of the initial ore shipment. Several other mines and open pits were started along the Offset, and they provided the bulk of the production from the district prior to 1900. The mining of the Offset deposits was discontinued in 1902 with the discovery and development of larger reserves available at the Creighton, Frood, and Stobie Mines.

The Copper Cliff Offset was explored extensively by the International Nickel Company from the early 1940s to the late 1960s and significant new reserves were blocked out. The Clarabelle Open Pit was developed in 1960 and mined out in 1977. Underground production started at the Copper Cliff North Mine in 1968 and at the Copper Cliff South Mine in 1969. It is estimated that the Copper Cliff Offset contains about 15% by weight of the known copper-nickel mineralization associated with the Sudbury Igneous Complex.

PREVIOUS GEOLOGICAL WORK

The earliest, and to date most comprehensive, description of the Copper Cliff Offset and its associated ore deposits is that of Coleman (1903, 1913). Coleman was the first to use the term "Offset"; he used this term rather than dike because of the irregularities in the dike and its numerous breaks and discontinuities along its length. Some of these discontinuities have resulted from later faulting, but most result from the initial intrusion of the Offset. Coleman noted the association of the ore deposits with the discontinuities in the Offset and he recognized the brecciated character of the country rocks adjacent to the Offset. He also recognized that the Offset rock was more altered and finer grained than the main norite, but he preferred to call it norite in order to emphasize what he believed to be a genetic link with the Sudbury Igneous Complex. Coleman also used the term "funnel" to describe the funnel-shaped norite embayment leading from the contact of the Sudbury Igneous Complex into the dike (see Figure 15.1).

Collins (1937) generally agreed with Coleman's description and conclusions, but he emphasized the mineralogical and textural differences between the

Copper Cliff Offset rock and that of the Main Mass of the Sudbury Igneous Complex. Collins agreed with Coleman that the dike was continuous with and, therefore, genetically related to the Sudbury Igneous Complex, but he thought that the differences in the silicate mineralogy had important genetic implications for the formation of the sulphide deposits. Collins favoured the term quartz diorite (termed Offset Sublayer in this volume) rather than norite for the Offset rocks.

Clarabelle Lake originally covered the connection between the funnel and the dike, and interpretation of diamond drilling results did not indicate a direct connection. The lack of a direct connection between the funnel and the dike, the difference in the mineralogy of the quartz diorite and the Main Mass of the Complex, and intrusive relationships between the quartz diorite dike and both the Creighton Pluton and the Sudbury Igneous Complex suggested to Yates (1948) that the quartz diorite dike and its associated ore deposits were intruded separately from the main Sudbury Igneous Complex. Subsequent mining, however, has shown that the dike and funnel are connected. Yates also believed that the orebodies in the dike were localized by folding and faulting.

Slaught (1951) examined the noritic rocks in the Copper Cliff Offset and concluded that the Offset is an apophysis of the main norite intrusive. Souch, Podolsky *et al.* (1969) described the orebodies and ore types in the Copper Cliff Offset. These authors introduced the term "Sublayer" to describe the sulphide- and inclusion-rich ore-bearing unit of the Complex, and classified quartz diorite as being one of the 3 Sublayer types. Pattison (1979) suggested that the Offset Sublayer was intruded before the Main Mass. He interpreted the Offset deposits as being emplaced by the outward injection of sulphide-rich melt resulting from meteorite impact.

GEOLOGICAL SETTING

A surface plan showing the general geology of the Copper Cliff Offset extending from the contact of the Sudbury Igneous Complex south to the Murray Fault system is shown in Figure 15.1. The Offset consists of 2 structural elements: the Copper Cliff funnel and the quartz diorite dike. The funnel is variable in width but generally narrows to the south and to depth until it joins the dike. The quartz diorite dike is approximately 40 m wide and generally dips vertically or steeply west. Its strike varies locally, but overall, the dike trends north-south. In this paper, the term Copper Cliff Offset refers to both the funnel and the dike, but the information and subsequent discussions will centre primarily on the quartz diorite dike.

The Copper Cliff Offset crosscuts the Huronian metavolcanic and metasedimentary formations, the

Creighton Pluton, and the Nipissing Diabase. The Copper Cliff Offset in turn is crosscut by narrow aplite dikes, west-trending quartz diabase dikes (often referred to as trap dikes), and northwest-trending olivine diabase dikes. The funnel and the quartz diorite dike are joined near surface but separated at depth (approximately 100 m); they remain separated down to the

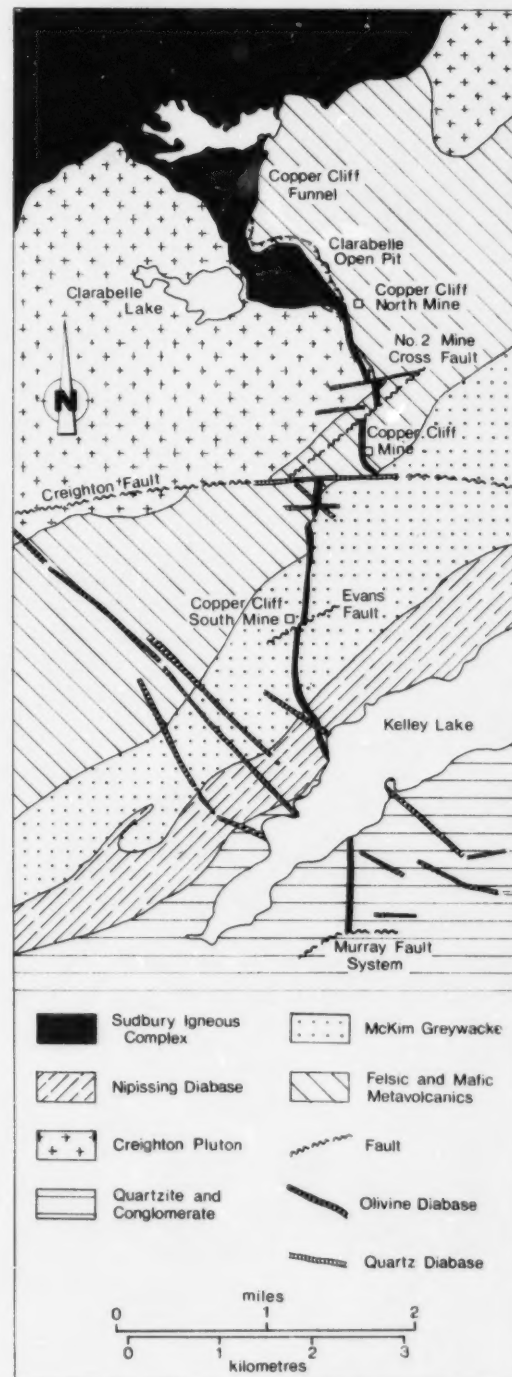


Figure 15.1. Surface geology of the Copper Cliff Offset.

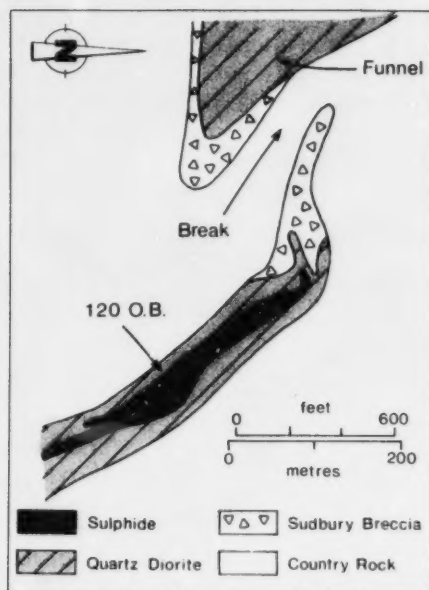


Figure 15.2. Plan of the 400-foot level, Copper Cliff North Mine, showing the break in the Offset between the funnel and the quartz diorite dike.

depth so far explored (Figure 15.2). Similar breaks and constrictions in the dike occur at several points along strike and down-dip (Figure 15.3). There is generally an increase in Sudbury Breccia in the Huronian Formation rocks adjacent to the dike; this brecciation is more prominent in the country rock at the breaks in the dike.

Structural Geology

The Copper Cliff Offset and the Huronian formations have been folded about northeasterly trending axes. The folds are open and the axial planes are generally vertical to steeply dipping. Folding in the quartz diorite dike is confined to that part south of the Creighton Pluton. The aplite, quartz diabase, and olivine diabase dikes have not been affected by the folding.

The Copper Cliff Offset is displaced at its southern end by faults associated with the main Murray Fault

(Figure 15.1), a major west-trending fault which has been traced from the Sudbury area west to Sault Ste. Marie (Card and Palonen 1976). The Offset has also been displaced by the Creighton Fault, a west-trending strike-slip fault which is part of the Murray Fault System. The fault strikes 080° and dips 75°N in the Copper Cliff area. The quartz diorite dike on the southern side of the fault is displaced approximately 700 m to the west. The Number 2 Mine cross fault strikes northeast, dips 60°NW , and is subsidiary to the Creighton Fault; it displaces the Copper Cliff Offset, the quartz diabase dikes, and the olivine diabase dikes. Movement was right lateral with approximately 20 m horizontal displacement of the Copper Cliff Offset. The Evans Fault strikes east-northeast and dips 40°S ; it separates the 800 orebody from the 810 orebody at the Copper Cliff South Mine. The displacement on the fault was also right lateral with a horizontal movement of about 30 m. The field relationships indicate that the faulting was the last geological event affecting the Offset and its associated sulphide deposits.

Petrography and Geochemistry of the Quartz Diorite

The modal composition of the Copper Cliff Offset quartz diorite consists of plagioclase 35 to 45%, amphibole 25 to 30%, quartz 10 to 15%, and biotite 10 to 20%, with minor amounts of granophyre and accessory apatite and sphene. Some of the amphiboles appear to be pseudomorphous after orthopyroxene. The biotite is a deep brown colour and is commonly found rimming the sulphides. The biotite content is much higher than in the quartz-rich South Range norite or the marginal Sublayer norite. The plagioclase crystals are zoned, their cores have a composition of An_{50} and their rims vary from An_{30} to An_{45} . Quartz is interstitial to the amphibole and plagioclase and shows optical continuity in thin section; such quartz is commonly termed "flood quartz".

The change from quartz diorite in the dike to Contact Sublayer is gradational in the funnel (Slaughter 1951). The Contact Sublayer differs from the quartz

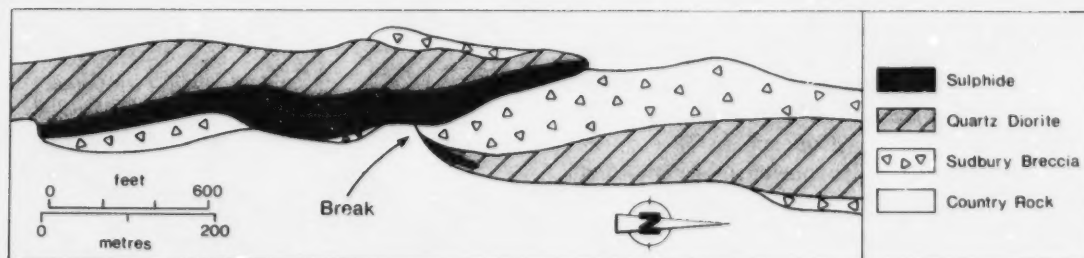


Figure 15.3. Plan of the 1250-foot level, Copper Cliff South Mine, showing the break in the quartz diorite dike.

diorite in that : (a) it is coarser grained, and the plagioclase crystals have a more blocky habit; (b) the plagioclase is slightly more calcic, reaching the labradorite composition; and (c) many of the plagioclase crystals show the dark cloudy colour of the South Range norite. Petrographically, the quartz diorite is finer grained and richer in biotite and amphibole than the Contact Sublayer, and at least some of the amphiboles are pseudomorphous after pyroxenes.

The chemical composition of samples taken from cores drilled through the dike at 4 locations is shown in Table 15.1 and the sample locations are shown in Figure 15.5. Specimens representative of each 6 m interval were combined and whole rock analysis was done by pressed pellet X-ray fluorescence at each intersection. The average composition of the samples of quartz diorite, the average composition of the lower zone of the Main Mass (Collins 1937), and an estimate of the original magma composition of the Main Mass (Cochrane 1982) are also shown for comparison. Although there is a variation in the chemical composition of the quartz diorite, the samples do not show any apparent trend either down-dip or along strike. Grant and Bite (Chapter 12, this volume) have shown that near the contact of the dike, the quartz diorite has been contaminated by the adjacent country rock. In general, the quartz diorite has a higher silica content, higher K_2O content, and lower MgO content than the estimate of the original composition of the Main Mass magma given in Table 15.1.

TABLE 15.1: CHEMICAL COMPOSITION OF THE QUARTZ DIORITE.

	1	2	3	4	5	6	7
SiO_2	60.61	60.64	58.80	60.68	58.18	55.16	55.6
Al_2O_3	15.32	15.13	14.93	14.97	15.25	16.86	16.0
* Fe_2O_3	2.38	2.38	2.42	2.37	2.26	1.94	2.1
* FeO	6.98	6.93	7.38	6.86	6.62	6.50	5.6
CaO	6.53	6.39	7.32	6.78	7.40	7.42	6.4
MgO	3.24	3.20	3.66	3.17	4.37	5.17	5.8
Na_2O	na	na	na	na	2.47	2.87	na
K_2O	1.72	1.76	1.34	1.46	1.89	1.35	1.5
TiO_2	.88	.88	.92	.87	.86	.83	.6

1—Sample located 3.2 km south of funnel, 900 m below surface

2—Sample located 50 m below sample 1

3—Sample located 3.5 km south of funnel, 700 m below surface

4—Sample located 3.8 km south of funnel, 2000 m below surface

5—Average of 3 samples of quartz diorite taken by Collins (1937)

6—Average composition of the lower zone of the Main Mass (Collins 1937)

7—Estimate of the initial composition of the Sudbury Main Mass (Cochrane 1982)

na—Not analyzed

* Fe_2O_3 and FeO calculated from total Fe using the method of Irvine and Baragar (1971)

Sudbury Breccia

Sudbury Breccia occurs in the country rocks adjacent to the dike and it is particularly abundant adjacent to the breaks in the dike. The breccias are important economically because adjacent to the mineralized quartz diorite, many of the breccias contain chalcopyrite-enriched sulphide stringers. The breccia has a fine-grained metamorphic-textured matrix consisting of granular quartz, feldspar, amphibole, and flaky chlorite with, in many places, scattered patches of recrystallized quartz and feldspar. The breccia fragments consist of amphibolites, gabbros, and metasedimentary rocks, which vary in diameter from a cm or so up to several m. Hawley (1962) has suggested that the quartz diorite magma has penetrated steeply dipping breccia zones opened up by tensional stresses.

Inclusions in the Quartz Diorite

The quartz diorite is characterized by zones containing numerous inclusions that form distinct mappable units, locally termed "inclusion quartz diorite". The inclusions can be divided into 2 groups according to size: those in the 1 to 2 cm range and those larger. Inclusions in the first group consist of amphibolites, metasedimentary rocks, anorthosites, and quartzites; these are normally subangular to subrounded, and are associated with weakly to moderately mineralized zones.

Larger inclusions generally consist of one of the following: gabbros, metapyroxenites and metaperidotites (exotic inclusions), norites, and quartz diorites. The inclusions are generally rounded to subrounded and are normally associated with the more heavily mineralized areas. Many of the quartz diorite inclusions are themselves weakly mineralized. The mafic and ultramafic inclusions are described by Naldrett *et al.* (Chapter 11, this volume).

MINERALIZATION

Mineralogy

The sulphides forming the orebodies along the Copper Cliff Offset have the same mineralogy as the marginal deposits along the basal contact of the Sudbury Igneous Complex. Pyrrhotite, pentlandite, and chalcopyrite comprise approximately 98% of the total sulphides. On the average, there is slightly more chalcopyrite than pentlandite in the dike mineralization. However, all orebodies show zoning of sulphide minerals and many zones are high in nickel.

Pentlandite occurs within the pyrrhotite in an exsolution texture, and also forms prominent "eyes" between the pyrrhotite grains in areas of more massive mineralization. Some of the pentlandite near the ground surface may show alteration to violarite.

Minor or accessory minerals include pyrite, cubanite, ilmenite, and magnetite that occur as follows: pyrite as small euhedral grains, cubanite as very thin exsolution lamellae in massive chalcopyrite, ilmenite and magnetite as euhedral blades and rods commonly altered to sphene.

Trace minerals, which have been observed in polished section, include sphalerite, galena, and gersdorffite. Cabri and LaFlamme (1976) reported michenerite (PdBiTe), sperrylite (PtAs_2), and sudburite (PdSb) in samples from the Copper Cliff South Mine.

Spatial Relationship of the Orebodies Along the Dike

Most of the mineralized zones associated with the funnel part of the Offset are located along the eastern contact (Figure 15.4). The bulk of the mineralization occurs within the Sublayer, but higher grade parts may form massive sulphide pods and lenses in the country rocks. As the mineralization in the funnel does not differ appreciably from that of the marginal deposits on the South Range, the orebody descriptions in this paper will concentrate on those occurring within the dike.

The mineralization in the dike is predominantly associated with inclusion quartz diorite; rarely is mineralization found crosscutting into Footwall rocks. The mineralization is not evenly distributed along the length of the dike. The ore zones, as shown in plan and longitudinal section in Figure 15.5, extend farther down-dip than along strike. In general, the ore zones contain at least 5% sulphides, and the areas between the orebodies consist of barren quartz diorite or weakly mineralized (2 to 3% sulphide) inclusion quartz diorite.

There are 9 main orebodies located along the dike between the funnel and Kelley Lake. From north to south, the orebodies are numbered 120, 100, 900, 880,

865, 850, 830, 810, and 800 (see Figure 15.5). The 865 and 880 orebodies are different parts of the same original ore zone now separated by the Creighton Fault. The 800 and 810 orebodies are considered to be parts of the 810 orebody, offset by the Evans Fault.

These orebodies can be divided into 2 types, depending on the location of the sulphides within the dike. In the first type, the sulphides are concentrated in the centre of the dike and form elongated pipe-like orebodies, with the ore separated from the country rock by barren quartz diorite. The 120, 100, and 900 orebodies are examples of this type and are referred to as "120 type orebodies".

In the second type, the sulphides are concentrated along the eastern side of the dike, with the sulphide content decreasing to the west. The 880, 865, 850, 830, 810, and 800 orebodies are examples of this type and are referred to as "810 type orebodies".

120 Orebody

The 120 orebody is located in the dike immediately south of the Copper Cliff funnel and is separated from it by a break (see Figure 15.2). At this point, the dike is approximately 40 m wide and dips either vertically or steeply eastward. The ore is contained within a 25 m wide zone of inclusion quartz diorite in the centre of the dike. The zone has a strike length of 200 m and extends to below the 4000-foot level. The quartz diorite dike follows the contact between the Creighton Pluton and the Huronian metavolcanic rocks, accounting for its vertical dip.

The distribution of the sulphides in the 120 orebody is shown schematically on a plan of the 1400-foot level (Figure 15.6) and on a longitudinal section (Figure 15.7a). In plan, the sulphides form a high grade core in the centre of the dike, surrounded by a lower grade fringe zone, which tails off to the south. The ore in each case consists of blebby disseminated sulphide in inclusion quartz diorite. This ore type, which is typical of the Offset orebodies, is described by Hawley (1965), Souch, Podolsky *et al.* (1969), and Naldrett (1969).

There are distinct differences in mineralogy and chemistry between the sulphide-rich ore and the sulphide-poor fringe. Assay data from approximately 500 diamond-drill samples were normalized to 100% sulphides assuming that all of the Ni was in pentlandite, all of the Cu in chalcopyrite, and the remaining sulphur in pyrrhotite. The sulphides in the core contain an average of 70% pyrrhotite, 14% pentlandite, and 16% chalcopyrite. Sulphides in the fringe zone have an average sulphide composition of 64% pyrrhotite, 15% pentlandite, and 21% chalcopyrite. The Pt, Pd, and Au content of the sulphides in the fringe zone is also higher.

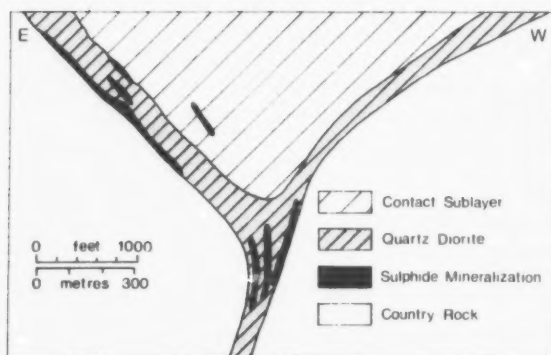


Figure 15.4. Cross-section through the Copper Cliff funnel, looking south.

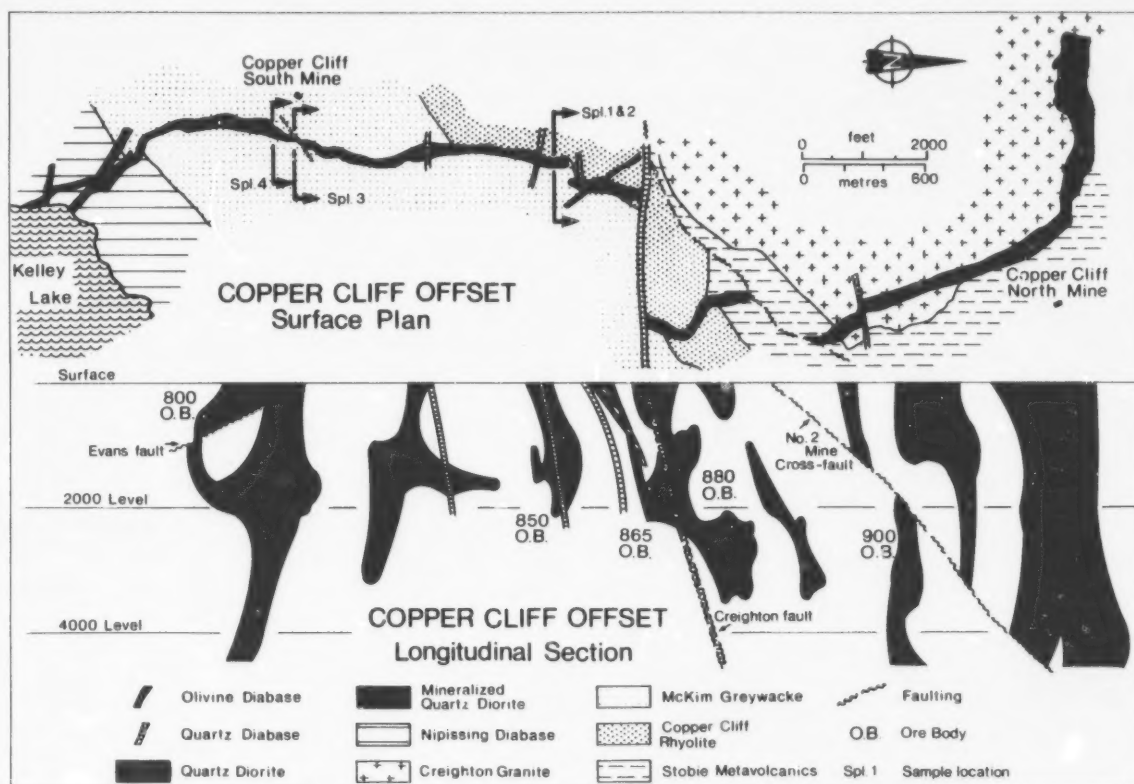


Figure 15.5. Plan and longitudinal section showing the distribution of the orebodies along the quartz diorite dike.

The longitudinal section (Figure 15.7a) shows that the sulphide content increases toward the centre of the ore zone and also increases with depth. In the upper levels of the orebody, the principal sulphide type consists of disseminated blebs of sulphide in inclusion quartz diorite. As the sulphide content increases with depth, the ore type changes to gabbro peridotite inclusion sulphide or inclusion massive sulphide.

The pentlandite and pyrrhotite content was calculated for each sample and normalized to 100%. The nickel grade was recalculated to 100% pentlandite and pyrrhotite to give Ni in iron-nickel sulphides. The results are plotted on a longitudinal section in Figure 15.7b. The observed pattern of lower nickel in the core than on the fringe reflects not the fact that the pentlandite content remains reasonably constant over the entire width of the orebody, but the fact that the pyrrhotite content increases in the sulphide-rich zone in the centre.

Variation in the chalcopyrite content of the sulphide is shown in Figure 15.7c. Chalcopyrite increases in the fringe areas, particularly at the southern end of the orebody and also to depth. Although not illustrated, assay information shows that the Pt, Pd, and Au content increases in these chalcopyrite-rich zones.

Naldrett (Chapter 13, this volume) discusses zoning at the Strathcona and McCreedy West Mines, 2 North Range contact type deposits. There is an increase in Ni, Cu, Pd, and Au from the Hanging wall Sublayer ore, through the Footwall Breccia to the Footwall ore. The 120 orebody demonstrates a similar zoning from the sulphide-rich core to the fringe areas and to depth. The zoning to depth is similar to the zoning in the Frood deposit as described by Hawley (1965). To explain this zoning, Naldrett (Chapter 13, this volume) favours fractionation of a monosulphide

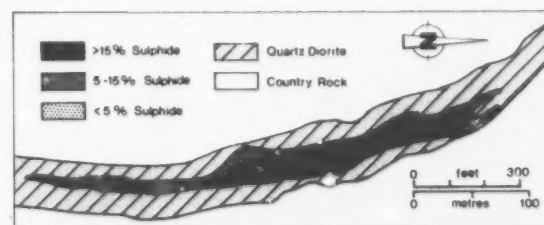


Figure 15.6. The 1400-level of the 120 orebody showing the distribution of the sulphide minerals.

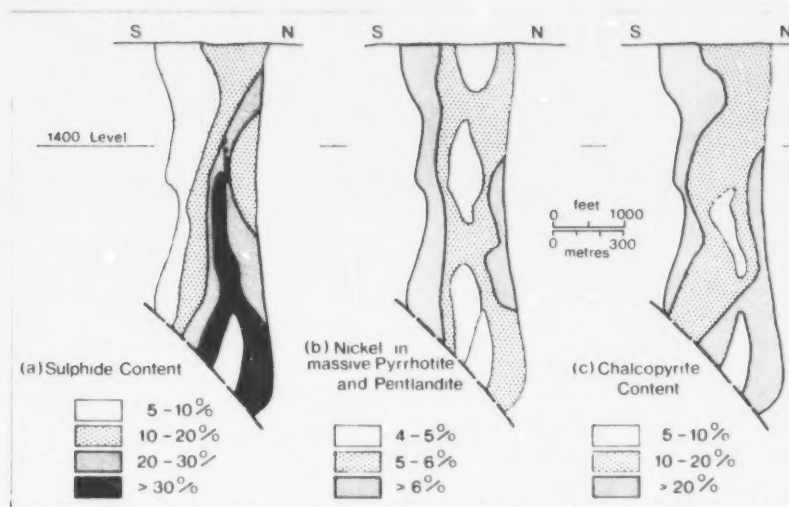


Figure 15.7. Longitudinal section through the 120 orebody showing: (a) the distribution of the sulphides; (b) the variation in the nickel content of massive pyrrhotite and pentlandite; (c) the variation in chalcopyrite content.

solid solution with enrichment of Cu, Pt, Pd, and Au in the sulphide melt. The residual sulphide phases enriched in these elements remain within the quartz diorite dike which contrasts with the North Range contact deposits where the higher copper zones intrude the adjacent country rocks.

810 Orebody

The 810 orebody is located approximately 3 km south of the 120 orebody and south of the Creighton Fault (Figure 15.5). It is only partly exposed on the surface because it lies below the Evans Fault (Figures 15.1 and 15.5). The 800 and 810 orebodies (Figure 15.5) were probably originally parts of the same orebody, but are now separated by the Evans Fault.

In the vicinity of the 810 orebody, the quartz diorite dike is approximately 60 m wide and the country rocks are metasedimentary rocks. The dike, ore, and metasedimentary rocks have been folded (Figure 15.8) with the result that the sulphides, which are located along the eastern contact of the dike with the metasedimentary rocks, now form the Hanging wall of the dike (Figure 15.8, 806 section).

The 810 orebody is located near a break in the dike as shown on the 1250-foot level plan (Figure 15.3) and in 814 cross-section (Figure 15.8). North of the break, the dike strikes north and contains only minor amounts of sulphide mineralization located within the centre of the dike. The dike south of the break strikes south-southeast and contains the 810 orebody. The 2 parts of the dike merge down-dip, but a flexure persists, marking the change in strike.

Assay data from approximately 800 diamond-drill samples were used to determine variation in sulphide content; variation in relative amounts of pyrrhotite, pentlandite, and chalcopyrite; and variation in the nickel content of the iron-nickel ore in plan and longitudinal sections.

The distribution of the sulphide content at the 1500-foot level is shown in Figure 15.9a. In general, the sulphide content increases from north to south and from west to east. Immediately south of the break, the sulphides occur as disseminated blebs in a zone of inclusion quartz diorite; farther south, the sulphide forms zones of inclusion massive sulphide along the eastern side of the dike, and at the extreme southern end, the sulphides are in the breccia zones adjacent to the dike. There are also zones of weakly mineralized, blebby disseminated sulphide in inclusion quartz diorite in the dike west of the main ore zone.

The Ni content in iron-nickel sulphides (Figure 15.9b) increases from north to south and is highest in the sulphide-rich part at the southern end of the orebody. The Ni content in the weakly mineralized west segments is somewhat erratic but is generally low.

The chalcopyrite content of the ore varies between 5 and 15%, but increases in the weakly mineralized segments along the western fringe of the orebody (Figure 15.9c). These segments are also enriched in Pt, Pd, and Au.

Variation in sulphide content with depth is shown in the longitudinal section in Figure 15.10a. The sulphide content increases to the centre of the orebody and down-dip, in a manner similar to the 120 orebody. Starting from the 1250-level break, the Ni content in

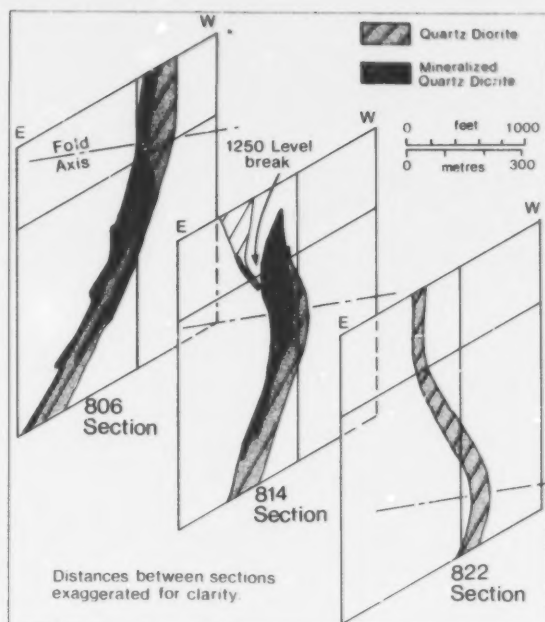


Figure 15.8. Cross-section through the 810 orebody showing the folding in the quartz diorite dike and the sulphides.

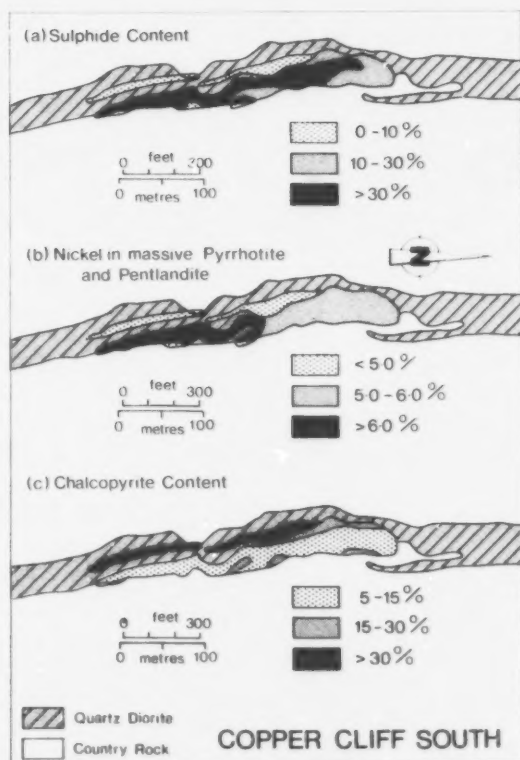


Figure 15.9. The 1500-level plan of the 810 orebody showing: (a) the distribution of the sulphides; (b) the variation in the nickel content in massive pyrrhotite and pentlandite; (c) the variation in the chalcopyrite content.

iron-nickel sulphides (Figure 15.10b) increases up-dip and to the south. Down-dip and south from the break it increases steadily over a considerable distance and then decreases very rapidly while the chalcopyrite content increases (Figure 15.10c). Although variation in chalcopyrite content of the ore is erratic, there is a general increase in the amount of chalcopyrite relative to pyrrhotite and pentlandite down-dip, up-dip, and to the south from the 1250-level break. The Pt, Pd, and Au are directly related to the chalcopyrite content.

There are minor chalcopyrite-rich sulphide stringers within the Sudbury Breccia zones at the southern end of the 810 orebody. However, as in the 120 orebody, zones richer in chalcopyrite generally remain within the quartz diorite.

The 810 orebody shows zoning trends which begin at the structural break in the dike at the 1250-level. A zone of inclusion quartz diorite with disseminated blebs of sulphide is located immediately south of the break. Farther south and down-dip, the mineralization consists of nickel-rich massive sulphide, located along the eastern contact of the dike. The distal parts of the orebody consist of chalcopyrite-rich sulphide stringers crosscutting the quartz diorite.

In the 810 orebody, the sulphides are concentrated along the eastern contact of the dike. The dike and the ore have been folded and, as a result, the dike dips to the east and the sulphides lie on the Hanging wall contact (Figure 15.8). In the 830, 865, and 880 orebodies, the dike dips from 70° to 50° W. The ore is located on the east dike/country rock contact which forms the footwall of the dike.

The attitude of the dike could provide an explanation for the difference in the zoning trends between the 810 type and 120 type orebodies. The early formed pyrrhotite-rich monosulphide blebs could have settled to the Footwall contact in the 810 type orebodies resulting in the formation of a copper-rich residual zone. In the vertically dipping 120 type orebodies, the pyrrhotite-rich monosulphide phase has remained in the centre of the dike.

Geochemistry of the Dike Orebodies

Representative samples from each orebody along the dike were analyzed for Cu, Ni, Co, S, PGMs, Au, and Ag. Table 15.2 gives the average sulphide content; the percent of chalcopyrite, pyrrhotite, and pentlandite relative to massive sulphide; the Co:Ni ratio; the Ag:Cu ratio; the Au:Cu ratio; and the ratio of Ru + Rh + Ir:Pt + Pd.

Along its strike, there are no distinct chemical trends in the orebodies within the dike. The geochemistry of the orebodies does not indicate any fractionation pattern related to the distance from the main

contact of the Sudbury Igneous Complex. There are, however, distinct geochemical differences between the 120 and 810 types.

The 810 type orebodies differ from those of the 120 type in the following ways: (a) they contain less pyrrhotite, (b) they have a lower Co:Ni ratio, (c) the ratio of Ru + Rh + Ir:Pt + Pd is lower, and (d) they have a higher Au:Cu ratio and Ag:Cu ratio.

The Distribution of the Sulphides in the Quartz Diorite Outside the Major Ore Zones

The core samples described previously were analyzed by aqua regia dissolution atomic absorption for Cu and Ni content. It is assumed in the following discussion that the Cu and Ni content is directly proportional to the sulphide content.

Figures 15.11a (Sample No. 4, Table 15.1) and Figure 15.11b (Sample No. 1, Table 15.1) show sections through the dike at 2 sample locations; at Figure 15.11a the dike is vertical, and at Figure 15.11b it dips 70°W. At both locations, the dike is approximately 35 m wide. The sample locations are shown in Figure 15.5.

In Figure 15.11a, there is a 5 m wide zone of inclusion quartz diorite in the centre of the dike. The inclusions are small (1 to 2 cm range), subrounded, and are made up of country rocks as previously described. The variation in the copper plus nickel content across the dike demonstrates the enrichment of the copper-nickel sulphides in the inclusion quartz diorite.

In Figure 15.11b, there are 2 zones of inclusion quartz diorite: (1) an 8 m wide zone in the centre of the dike and (2) a 2 m wide zone along the Footwall contact on the eastern side of the dike. The inclusion population is the same in both zones and similar to the inclusions within the inclusion quartz diorite shown in Figure 15.11a. The Cu-Ni sulphides are enriched in both inclusion quartz diorite zones, reaching a high of approximately 2500 ppm in the central zone and rising to approximately 5000 ppm in the Footwall zone. The average Cu plus Ni content in the inclusion-free quartz diorite is 200 ppm, corresponding to a sulphur content of < 0.1%.

The concentration of Cu and Ni sulphides within the inclusion-bearing quartz diorite is typical of other locations along the length of the dike. It is also similar to the association of sulphides within inclusion-bearing Sublayer norite along the basal contact of the Sudbury Igneous Complex.

DISCUSSION

The quartz diorite has been defined as a phase of the Sublayer by Souch, Podolsky *et al.* (1969). Field evidence shows that it grades into the Contact Sublayer in the funnel part of the Copper Cliff Offset. Ore deposits along the dike part of the Offset occur within the quartz diorite and have the same general sulphide mineralogy as the marginal deposits. The similarity between the sulphides of the dike deposits and those of the marginal deposits at the contact of the Sudbury Igneous Complex, together with the physical continuity (gradational change) of the quartz diorite with the Contact

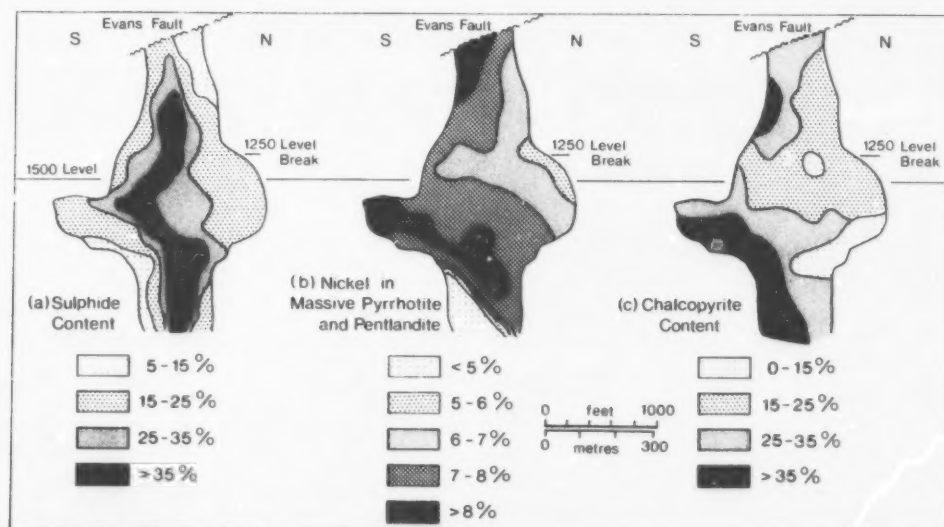


Figure 15.10. Longitudinal section through the 810 orebody showing: (a) the distribution of the sulphides; (b) the variation in the nickel content in massive pyrrhotite and pentlandite; (c) the variation in the chalcopyrite content.

Sublayer phase indicate that the Offset and contact deposits have been derived from the same source.

The "barren" or essentially unmineralized quartz diorite contains approximately 200 ppm Cu plus Ni and < 0.1 % sulphide by weight.

Sulphide concentration up to 5 % by weight is associated with zones of inclusion quartz diorite. These inclusion-bearing zones are generally found in the central part of the dike, but can occur throughout the dike. The central location of the inclusion-bearing quartz diorite could be the result of flowage differentiation whereby the inclusions have migrated toward the higher velocity region in the centre of the dike (Bhattacharji and Smith 1964).

The relationship of the sulphides to the inclusions is uncertain. Naldrett and MacDonald (1980) discussed the effect on the sulphur solubility of a magma by adding silica. Increased silica causes a decrease in the solubility of sulphur resulting in the formation of a sulphide melt. Barker (1975) described the sulphide and inclusion-rich basal zone of the Stillwater Complex. He found that the hornfels inclusions were deficient in considerable amounts of SiO_2 and minor amounts of Na_2O , K_2O , and H_2O , all of which had been released into the enclosing sulphide-rich magma. There is, however, at the present time, no direct evidence to indicate that local silica contamination of the quartz diorite in the inclusion-bearing zone has resulted in the deposition of the sulphides. The sulphides could also have been concentrated with the inclusions due to flowage differentiation.

The concentration of the mineralization into lenses or pods of economic grade ore appears to be related to constrictions in the dike, often in the form of actual breaks. These constrictions appear to have provided a structural trap for sulphide accumulation. The dike

area immediately "down stream" from a break in the direction of magma flow would provide a relatively stable environment for sulphide concentration in a manner similar to the Footwall troughs containing the Contact Sublayer at the margins of the Sudbury Igneous Complex.

Both the 120 and 810 type orebodies show chemical and mineralogical zoning. Sulphide nearest the breaks forms pyrrhotite-rich blebby disseminated sulphides in inclusion quartz diorite. Moving toward the south and down-dip, the sulphide content increases, forming pods of inclusion massive sulphide containing the highest grade nickel ore. Moving farther to the south and down-dip, the extremities of the orebodies consist of chalcopyrite-rich stringers crosscutting weakly mineralized inclusion quartz diorite. These stringers are also enriched in Pt, Pd, and Au.

Hoffman *et al.* (1979) reviewed possible explanations for the zoning in the McCreedy West deposit which included: 1) late stage hydrothermal remobilization; 2) fractionation of a sulphide melt; and 3) diffusion of mobile elements along a thermal gradient induced by the overlying Sudbury Igneous Complex. Citing field evidence and experimental data, Naldrett (Chapter 13, this volume) favours fractional crystallization of a sulphide melt to explain chemical and mineralogical zoning in many Sudbury ore deposits. This explanation is also favoured to explain the zoning trends exhibited by the sulphides in both the 120 and 810 type orebodies.

The differences in the sulphide chemistry of the 120 and 810 type orebodies (Table 15.2) appear to be related to the attitude of the host quartz diorite dike. The 810 type ore zones are enriched in Cu, Ni, Pt, Pd, Au, and Ag, but depleted in Co, Ru, Rh, and Ir when compared to the 120 type orebodies. The 810 ore zones

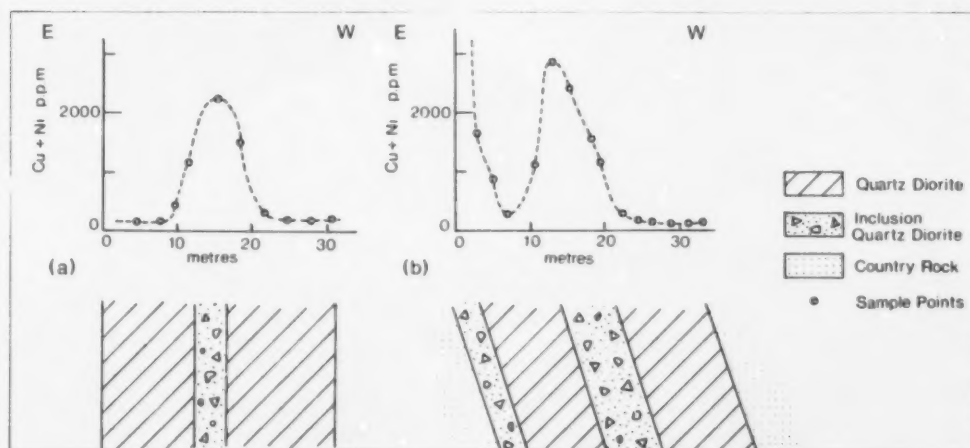


Figure 15.11. Relationship of the copper plus nickel distribution to the silicate differentiation showing the influence of the dip of the dike.

TABLE 15.2: GEOCHEMISTRY OF THE OREBODIES IN THE QUARTZ DIORITE DIKE.

OREBODY	OREBODY TYPE	LEVEL INTERVAL SAMPLED	AVERAGE SULPHIDE CONTENT	% Pb (100% SULPHIDE)	% Pb	% Cu	Co / Ni	Ag / Cu	Au / Cu	flu + Rh + Ir Pt + Pd
100	120	0-2000	19	75	12	13	0.048	0.48×10^{-3}	18×10^{-9}	0.30
900	120	400-1200	22	80	12	8	0.054	0.49×10^{-3}	19×10^{-9}	0.34
865	810	500-2050	24	63	17	20	0.035	0.53×10^{-3}	22×10^{-9}	0.08
830	810	500-2050	18	65	17	18	0.032	0.65×10^{-3}	27×10^{-9}	0.12
810	810	500-3000	33	65	17	18	0.029	0.63×10^{-3}	27×10^{-9}	0.10

are enriched in those elements which are concentrated in the late-crystallizing sulphide phases. Gravitational separation of a nickel-rich monosulphide phase along the footwall of the dike would allow a more complete separation of a copper-rich phase, possibly allowing a longer time period for chemical interaction with the quartz diorite magma and more efficient removal of the low melting point elements.

Full understanding of the cause and character of the fractionation process requires a knowledge of: 1) what constitutes a complete orebody; 2) the initial composition of the silicate liquid with which the sulphides have equilibrated; and 3) the influence of the structural environment where sulphide deposition took place.

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Much of the paper is based on surface and underground maps compiled by the many geologists who have worked at the Copper Cliff North and Copper Cliff South Mines and on research reports by the Inco Limited Geological Research group. I particularly wish to thank E. Wohlberg and D. Stephenson for their valuable contributions. Numerous improvements to the paper were suggested by R. Tate, N.L. Anderson, W.V. Peredery, A.C. Gourley, R.A. Alcock, H.O. Harju, and J.A.E. Allum. K.A. Randall provided computer programming assistance, L. Kurkimaki typed the many manuscripts, and L.S. Fajcz prepared the diagrams. The paper is published with the permission and support of Inco Limited.

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CHAPTER 16

Little Stobie Mine: A South Range Contact Deposit

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ABSTRACT

The Little Stobie Mine is described as embodying characteristics of the Sudbury District South Range contact ore deposits. The South Range contact deposits occur in depressions within the Footwall of the Sudbury Igneous Complex or as protrusions into the Footwall immediately adjacent to this contact. The orebodies are distributed along a northeast-striking norite-Footwall contact and dip variably between 45°N and 85°S. They are composed of a regular sequence of sulphides, within the Sublayer, and consist, from hanging wall to footwall, of interstitial sulphide, ragged disseminated sulphide, gabbro-peridotite inclusion sulphide, inclusion-bearing massive sulphide, and massive sulphide. Pyrrhotite, pentlandite, and chalcopyrite are the primary sulphide minerals.

The Little Stobie Mine contains this sequence in 2 orebodies—The Number 1 and the Number 2. The Number 1 orebody occurs in a shallow embayment on the norite contact within the Sublayer and extends some 610 m in length. The Number 2 orebody protrudes at right angles to the Number 1 some 520 m into the Footwall. This orebody is intimately related to a zone of Footwall Breccia which is controlled by a granite-“greenstone” contact. The typical South Range ore sequence is present, but somewhat jumbled above the 1200 Level. There is a zoning of minerals and metals with the pyrrhotite, chalcopyrite, and precious metals concentrated toward the Footwall in the Number 1 orebody, and an enrichment of precious metals in the Number 2 orebody increasing in value with depth into the Footwall. Details of assays of 12 900 samples are given showing this distribution. All ore and rock types

have been affected by later cross faulting.

The orebodies are seen to be similar to a typical South Range deposit, but have been rearranged by post-ore adjustments. These adjustments squeezed ore from the Number 1 orebody above the 1200 Level into the Number 2 orebody position and coincidentally effected partial mixing of the remaining parts of the Number 1 orebody above the 1200 Level. The ore below the 1200 Level is considered to be a typical Sudbury South Range assemblage.

SOUTH RANGE CONTACT DEPOSITS

The South Range contact deposits extend from the Chicago Mine on the west, to the Falconbridge Mines on the east. These deposits are characterized by a footwall composed of volcanic, sedimentary, and granitic rocks of Huronian age and a hanging wall of quartz-rich norite.

The South Range contact is economically the most important section of the Sudbury District, hosting no less than 17 present or past producing mines and many minor mineral occurrences. Production from one or more of the properties has continued virtually without interruption since their initial discovery in 1883. The major present and past producers include Crean Hill, Lockerby, Creighton, Murray, McKim, Little Stobie, Blezard, Kirkwood, Garson, Falconbridge, and Falconbridge East Mines. The Garson, Falconbridge, and Falconbridge East Mines are considered to be special cases of South Range contact deposits. The first 2 are discussed elsewhere in this volume.

South Range contact deposits occur in depressions or embayments in the Footwall of the Sudbury Igneous Complex or as protrusions into the Footwall immediately adjacent to this contact. The hanging wall is almost invariably quartz-rich norite (Souch, Podolsky *et al.* 1969; Naldrett *et al.* 1972), while Footwall rocks consist of the metavolcanic and metasedimentary rocks of the Elsie Mountain and Stobie Formations, or the Creighton and Murray Plutons (*see* Map 2491, back pocket). All of the Footwall rocks have been brecciated to form Sudbury Breccia (Speers 1957) and have been metamorphosed to the greenschist and amphibolite facies.

The norite contact on the South Range trends between N45°E and east over a 60 km length. Dips vary along the contact, but are generally steep, that is 80°S and 80°N at the eastern and western ends, respectively, and 45°N to 70°N in the central part. There are local irregularities in the attitude of the contact in the vicinity of the embayments and where the Offset Dikes leave the Sudbury Igneous Complex and penetrate into the Footwall.

Ore Deposits

The contact ore deposits of the South Range occur in 2 distinct environments: (1) on the contact between the norite and the Footwall, or (2) as protrusions into the Footwall.

The contact deposits are uniform from mine to mine. A general increase in the sulphide content from the norite Hanging wall to the Huronian Footwall has been noted by previous authors: Souch, Podolsky *et al.* (1969), Yates (1938), Coleman (1913), and Knight (1917). The characteristic sequence of ore types from Hanging wall to Footwall is: interstitial sulphide, ragged disseminated sulphide, gabbro-peridotite inclusion sulphide, inclusion-bearing massive sulphide, and massive sulphide. This sequence was first identified at the Creighton and Murray Mines and is now known to apply generally to other South Range contact deposits.

The protrusions of ore into the Footwall can extend for distances of up to 600 m. These orebodies contain the same ore types as the contact deposits and are generally connected to them. The orebodies are typically enriched in copper, nickel, and precious metals, as well as total sulphide, in comparison to the contact deposits.

The sulphide mineralogy is monotonously uniform; combined pyrrhotite, chalcopyrite, and pentlandite form 95% of the total, with pyrite and cubanite locally abundant.

Most orebodies of the South Range show some deformation features such as primarily shearing, but also show folding, fracturing, and brecciation.

The Little Stobie Mine will be described in detail as a representative South Range deposit.

LITTLE STOBIE MINE

The Little Stobie Mine is located in Blezard Township on the South Range of the Sudbury Igneous Complex approximately 4.8 km north of the City of Sudbury. The deposit was discovered in 1885 by James Stobie, a pioneer prospector. The discovery was followed by limited production of ore from shallow shafts and pits until 1905. In 1930, the then dormant property was acquired by the International Nickel Company (presently Inco Limited) and was ultimately brought into production in January 1971.

The Little Stobie deposit occurs in a shallow embayment at the base of the Sudbury Igneous Complex. The contact in this area strikes N60°E and dips 55° to 70°NW. The embayment is occupied by a thick zone of Sublayer that extends for a strike length of 670 m and projects into Footwall for as much as 520 m. The average width of the Sublayer is 90 m. The orebodies oc-

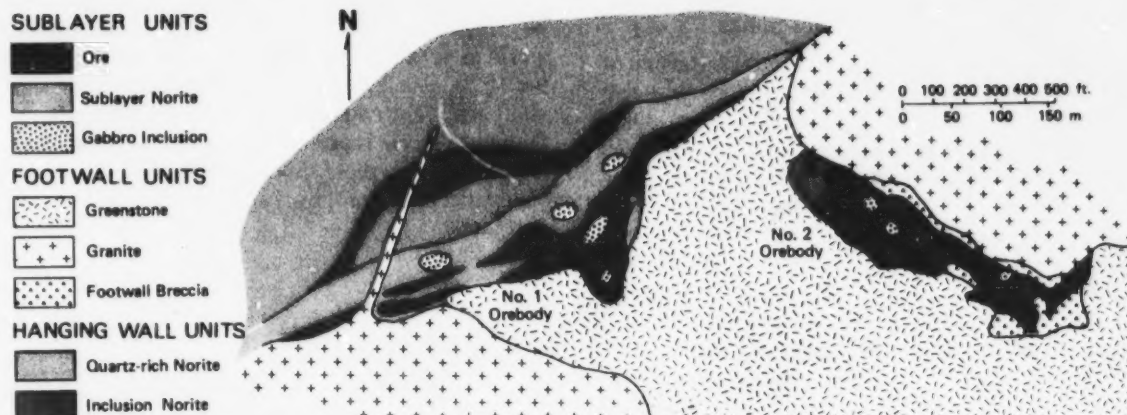


Figure 16.1. Little Stobie—Generalized Underground Plan.

cur as sulphide-enriched parts of the Sublayer, with the immediate hanging wall consisting of quartz-rich norite, the footwall of rocks of the Murray Pluton, or metavolcanic rocks of the Elsie Mountain Formation.

Two distinct orebodies are recognized (Figure 16.1). The Number 1 orebody occupies the contact of the embayment and extends along the contact for approximately 610 m. The average width is 30 m and sulphide mineralization is continuous from the surface to a depth of at least 1000 m. The Number 2 orebody forms an appendage almost perpendicular to the Number 1 orebody, between the 300-foot and 1200-foot levels, and strikes S60°E into the footwall rocks for approximately 520 m. Ore widths are variable with an average of 53 m. Most South Range ore types are present at Little Stobie. The principal ore minerals are the usual Sudbury assemblage of pyrrhotite, chalcopyrite, and pentlandite.

Hanging Wall Rocks

The immediate hanging wall rocks of the Little Stobie deposit are quartz-rich norite and inclusion-rich norite. The quartz-rich norite is a medium- to coarse-grained, generally poikilitic rock which is readily recognized by its coarse texture and abundant blue opalescent quartz. It contains 10 to 20% anhedral interstitial quartz, zoned laths of plagioclase, zoned hypersthene, augite, primary hornblende, and biotite (Naldrett *et al.* 1970).

At Little Stobie, the quartz-rich norite is continuous over the entire length of the hanging wall and is in sharp contact with the footwall rocks at the extreme eastern and western ends of the mine, where the Sublayer is absent. The contact between the quartz-rich norite and Sublayer is variable in nature. Generally, it is gradational over a width of 1 m, but in places it is sharp. The norite at the contact frequently contains

some sulphide in the interstices between cumulus crystals of plagioclase and/or pyroxene (Duke and Naldrett 1976). Where this occurs, the ore type is called interstitial sulphide (Souch, Podolsky *et al.* 1969). Mineable widths up to 6 m occur at Little Stobie with the greatest development of this ore type where the Sublayer is thickest.

The inclusion-rich norite forms an irregular, convex zone which crosscuts the quartz-rich norite and joins the Sublayer at the eastern and western parts of the mine. The central part of the zone projects a maximum of 90 m into the hanging wall (Figure 16.1). The unit has a base length of 335 m, varies in width from 15 to 61 m, and dips 60° to 70°NW.

The matrix of the inclusion-rich norite has a composition similar to the quartz-rich norite, but has a higher sulphide content (approximately 5% disseminated sulphide blebs). The inclusions are generally hornfelsic and include basic and anorthositic rocks. The inclusion content is variable, but generally is estimated to be over 50% of the total rock. Where the inclusions are rounded, the inclusion content increases to 70%. Two types of inclusions are recognized. The first consists of well rounded pebbly inclusions, 2 cm in diameter, found in the limbs of the arc close to the Sublayer. The second consists of platy, lenticular inclusions, 0.5 to 2.5 cm wide and 2.5 to 15 cm long, and predominate toward the crest of the arc. The platy, lenticular inclusions are generally aligned parallel to the trend of the arc and dip northwest. Contacts between inclusion norite and quartz-rich norite are well defined by the frequency of inclusions.

Footwall Rocks

The immediate footwall rocks of the Little Stobie deposit consist of the Elsie Mountain metavolcanic rocks,

the Murray Pluton, and an isolated granite plug, locally called the Number 2 orebody granite.

The Elsie Mountain Formation is the basal unit of the Elliot Lake Group of the Huronian Supergroup. It is the oldest rock unit in the mine environment. On a regional scale, the unit consists mainly of metamorphosed basalt flows which dip vertically and face uniformly southward. The metabasalt is mainly medium to coarse grained, dark green to black, equigranular or foliated, consisting of amphibole (hornblende and actinolite), plagioclase (An_{20} to An_{40}), quartz, and chlorite. The rock has undergone recrystallization under conditions corresponding to the greenschist and amphibolite facies of regional metamorphism (Card 1978). The local name for this unit is "greenstone". At Little Stobie, the Elsie Mountain Formation forms the footwall for the eastern part of the Number 1 orebody and the western side and bottom of the Number 2 orebody. It is a complex unit ranging from coarse-grained amphibolite to fine-grained hornfels, the predominant unit being a fine- to medium-grained, dark green amphibolite. The attitude of the unit here has not been determined because of extensive Sudbury brecciation. The hornfels, locally called sudburite, is a strongly magnetic, fine-grained, grey-green, pyroxene-rich rock, laced with streaks of fine-grained secondary amphibole developed along fractures. This unit occurs as large masses and as smaller inclusions within the medium-grained amphibolite. The sediments of the Elsie Mountain Formation are not well represented in the mine area. These rocks occur mainly as isolated zones within the "greenstone" and consist primarily of dark grey, arkosic quartzite. These sediments appear to be blocks in the "greenstone" rather than interflow beds.

The Elsie Mountain Formation is intruded by rocks of the Murray Pluton that are pink, medium-grained, equigranular rocks consisting of microcline perthite moulded around quartz, irregular grains of oligoclase (An_{28}), minor subhedral albite, brown biotite, sphene, epidote, and zircon (Hawley 1962). An "offshoot" dike of this "granite" in the western part of the mine penetrates into the norite for a distance of 360 m (Speers 1957). Gibbins and McNutt (1975) have dated the main Murray Pluton at 2.26 Ga and the offshoot at 1.7 to 1.8 Ga. This supports the hypothesis that the main "granite" is pre-norite and the offshoot is post or contemporaneous with the norite.

In the mine sequence, rocks of the Murray Pluton form the footwall of the western part of the Number 1 orebody (Figure 16.1) where it appears as a massive unit in contact with the sublayer and the "greenstone". It contains isolated blocks of "greenstone" and rare stringers of sulphide. The "greenstone"- "granite" contact strikes N60°W and dips 80°NE. The "granite" is known to extend to depths of 960 m and the offshoot to depths of 450 m.

The Number 2 orebody granite is compositionally similar to the Murray Pluton, but is smaller in size and does not extend above the 300-foot level (see Figure 16.3). The 2 granite bodies have a minimum separation of 270 m and do not appear to connect at depth. Sudbury Breccia is extensively developed on the contacts of both granites, although the intensity of brecciation decreases progressively from the contact into the granite.

Sublayer

At Little Stobie, the Sublayer unit strikes N60°E for 670 m with dips of 55° to 70°NW. The widths of this zone are variable but average 90 m. The Number 2 orebody part strikes S60°E into the Footwall rocks for a maximum distance of 520 m. The dip is near vertical and the unit extends from the 300-foot to the 1200-foot levels.

The Little Stobie Sublayer is comparable to that of other South Range deposits as described by Souch, Podolsky *et al.* (1969). The contained sulphide minerals, comprising the normal Sudbury assemblage of pyrrhotite, chalcopyrite, and pentlandite, form massive, stringer, and disseminated ores.

The inclusion population is predominantly 2-pyroxene gabbro, but inclusions of ultramafic rocks, quartz-rich norite with interstitial sulphide, and footwall rocks are also found. The gabbro inclusions consist essentially of poikiloblastic plagioclase, hornblende, clinopyroxene, and orthopyroxene, and occur as variably sized, rounded to subrounded inclusions ranging from 2 cm to 46 m in diameter. Most of these inclusions are barren, but some contain sulphide, either as fracture fillings or as fine disseminations. The ultramafic inclusions, mainly pyroxenites and peridotites, are small, rounded, and altered. They often exhibit reaction rims of amphibolite, talc, chlorite, or biotite. Quartz-rich norite inclusions, with interstitial sulphide, occur as angular blocks up to 5 m thick. Most footwall rock inclusions have been derived from the metavolcanic rocks of the Elsie Mountain Formation. These inclusions are generally small, 2 cm to 5 m across, but locally range up to 9 m in size. Granite inclusions are rarely found in the Sublayer.

The Sublayer norite matrix hosting these inclusions is fine to medium grained, weakly to moderately siliceous and biotitic. On the average, the matrix consists of 46% zoned lathy plagioclase, 25% prismatic to subophitic clino and orthopyroxene, 7% biotite, 9% hornblende, and 13% quartz.

The contact of the Sublayer with the hanging wall is generally gradational, while the contact with footwall rocks is abrupt. At the eastern and western extremities of the mine, the Sublayer pinches out.

Number 1 Orebody

The Little Stobie Number 1 orebody epitomizes the Sudbury South Range contact deposit. The ore constitutes approximately 20% of the total volume of Sublayer in the Little Stobie embayment. The largest part of the orebody, and by far the most important economically, consists of a filling of the deepest part of the Little Stobie embayment. Most of this ore is located at, or close to, the footwall contact, or as stringers extending a short distance into the footwall (Figure 16.2). The rest of the orebody consists of narrow lenses of ore extending to the west of this deep zone (Figure 16.1). Here, the ore may occur on the footwall, as lenses and stringers within the Sublayer, or rarely on the contact between Sublayer and quartz-rich norite. All ore tends to pinch and swell, to be interrupted by the Sublayer inclusions, and to increase or decrease in grade with little discernible pattern.

The Number 1 orebody is 610 m long and averages 30 m wide at surface with the dimensions decreasing with depth. The ore zone has been extensively tested to 1000 m. Boundaries of economic mineralization with the Sublayer are not sharply defined, but are gradational in nature. Where the ore rests directly on the footwall, contacts are sharp except for sulphide stringers that penetrate the footwall for short distances. The footwall/ore contact undulates with dips ranging from steep to almost horizontal. The flat dipping sections tend to be overlain by a thicker sulphide sequence.

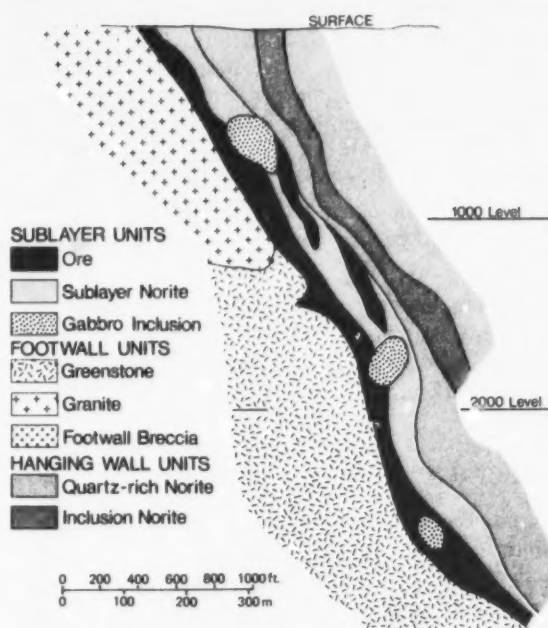


Figure 16.2. Little Stobie Number 1 Orebody—Generalized Cross-Section Looking West.

The Number 1 ore zone contains most of the typical South Range ore types described by Souch, Podolsky *et al.* (1969). There is a crude zonation of ore types within the orebody with the more sulphide-rich zones located closest to the footwall, and weaker sulphide mineralization located toward the hanging wall. Most ore types can be found as stringers or bands crosscutting all other ore types or as inclusions within each other, except for inclusion massive sulphide which generally occurs as stringers in the footwall or immediately adjacent to the footwall contact.

Gabbro peridotite inclusion sulphide (GPIS) is the most abundant ore type in the Number 1 orebody. It consists of various gabbro or hornfels inclusions in a matrix of sulphide and minor amounts of Sublayer norite. Some footwall inclusions may be present near the footwall contact. Inclusion sizes range from 0.5 cm to 10 m in diameter. The inclusions are generally fresh and unaltered, but can have a thin selvage of chlorite and occasionally contain finely disseminated sulphide (mainly chalcopryrite). Within any given area, most inclusions are of the same rock type. Within the orebody, the GPIS forms elongate lenses, continuous for up to 120 m, which pinch, swell, and wrap around larger rock zones that in themselves are inclusions within the Sublayer. Because of the nature and extent of GPIS throughout the orebody, it is not normally recognized as inclusions within other ore types.

Ragged disseminated sulphide (RGDI) is the second most abundant ore type. It contains less sulphide and more norite in the matrix than the GPIS. The inclusions are similar to those of the GPIS but significantly smaller (in the order of 2 cm in diameter), and more altered. Typically, the cusped masses of sulphide and norite act as an irregular matrix surrounding the packed inclusions. In places, there is a tendency for the sulphide to be preferentially concentrated on one side of the inclusions. The RGDI ore type is found throughout the orebody both as long continuous zones and as distinct blocks within the GPIS. Contacts are sharp where the unit is a block, and gradational with the GPIS where it has larger dimensions.

Massive sulphide and inclusion massive sulphide are usually located along the footwall contact, or as stringers penetrating the footwall. Volumetrically, these ore types constitute a small proportion of the orebody. The inclusions, where present, are of the same rock type as the immediately adjacent footwall. Massive sulphide stringers penetrate the footwall rocks for up to 60 m, with the width of the stringers tapering off into the footwall. These stringers are characteristically enriched in chalcopryrite and precious metals with respect to the orebody in general. A massive sulphide slab, 10 m long, has been reported within quartz-rich norite (Pattison 1979), and massive sulphides have also been observed as subrounded fragments (10 cm in

maximum dimension) within GPIS and RGDI (probably a variety of fragmental and disseminated sulphide). This fragmental feature is noted primarily in the area known as the "cross-over" between the Number 1 and Number 2 orebodies.

Interstitial sulphide in quartz-rich norite (INSU) has two modes of occurrence within the Number 1 orebody. It occurs sporadically in the lower 6 m of the quartz-rich norite, and also as irregular, angular blocks within RGDI and GPIS ore types. Economically, it is a relatively unimportant ore unit.

Contorted schist inclusion sulphide is rare within the Number 1 ore zone where it is associated with post-ore crosscutting shears.

Number 2 Orebody

The Number 2 orebody occurs within the footwall adjacent to the main Little Stobie deposit (Figure 16.1) It forms a tabular dike-like deposit connected to the Number 1 orebody between the 400-foot level and 875-foot level, and projects some 520 m into the Footwall between the western contact of the Number 2 orebody granite and a massive part of the "greenstone". The ore zone averages 50 m in width and extends from 60 to 360 m below surface. The strike is $S60^{\circ}E$ and dips are generally vertical but flatten considerably where the zone rolls over the top of the granite. Sixty percent of the Sublayer is ore (Figures 16.1 and 16.3).

The orebody has been emplaced into a zone of Footwall Breccia similar to that described by Pattison (1979). This Breccia consists of basic fragments (essentially amphibolites of footwall derivation) enclosed in a light grey to dark green matrix. Recrystallization has resulted in a matrix ranging from a fine-grained intergrowth of quartz and feldspar to a

medium-grained equigranular rock which also has well developed biotite, amphibole, or pyroxene porphyroblasts. Sulphide occurs within the matrix as randomly scattered disseminated blebs, or as rounded to subrounded fragmental appearing patches. The breccia occurs primarily as a sheath around the Number 2 orebody or as inclusions within the ore zone. In the more distal part of the Number 2 orebody, the matrix is more siliceous, whereas close to the norite contact it is more basic in composition.

The Number 2 orebody is irregular in shape close to the "cross-over" area and in the upper sections of the ore zone. In the lower and distal parts of the zone, the ore is more continuous, the inclusions are smaller, and the Sublayer is more strongly mineralized.

The ore is composed of 2 major Sudbury ore types. Gabbro peridotite inclusion sulphide (GPIS) is by far the most abundant. It is the predominant ore type in the "cross-over" zone, occurs on the western flank of the ore zone above the 600-foot level, and is the major constituent of the orebody below the 600-foot level. It is virtually identical to the GPIS of the Number 1 orebody with respect to the sulphide and inclusion types. The majority of the inclusions are gabbro with some metapyroxenite. The proportion of talcose ultramafic inclusions is slightly higher than in the Number 1 orebody.

The other major ore type present in the Number 2 orebody is a form of blebby disseminated sulphide which consists of elongated blebs of sulphide in a matrix of highly altered Sublayer norite. In some areas, the matrix resembles that found in the Footwall Breccias. The sulphide blebs tend to flow around elongated or disc shaped gabbro, gabbro hornfels, or Footwall Breccia inclusions. The generalized trend of this foliation is parallel to the long axis of the ore zone. A non-foliated form of disseminated sulphide also occurs in minor amounts within the ore zone. Contacts with the GPIS ore type are generally sharp, but age relationships between the 2 have not been determined. This ore type is almost exclusively found above the 600-foot level.

Minor amounts of contorted schist inclusion sulphide are associated with late shearing within the Number 2 orebody. There are no blocks of interstitial sulphide in quartz-rich norite within the Number 2 orebody.

Mineral and Metal Distribution

A crude zonation is apparent within the 2 orebodies. There is an increase in sulphide content toward the footwall in the Number 1 orebody and a corresponding increase toward the distal and lower parts of the Number 2 orebody. On average, the Number 2 orebody has a greater proportion of sulphide and higher copper and nickel values than the Number 1 orebody.

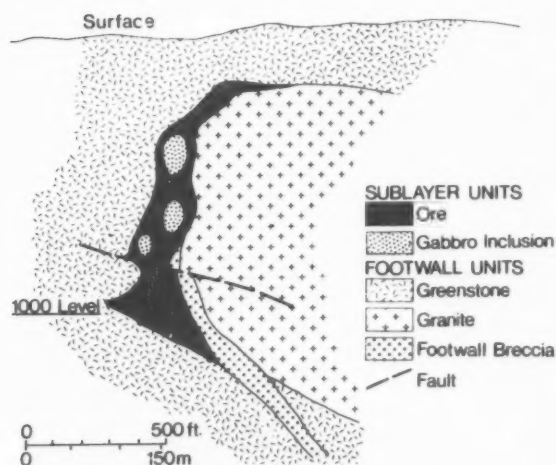


Figure 16.3. Little Stobie Number 2 Orebody—Generalized Cross-Section Looking North.

TABLE 16.1: METAL DISTRIBUTION—NORMALIZED TO 100% SULPHIDE.

BLOCK**	OREBODY	% Cu	% Ni	% Co	% S	Pt*	Pd*	Au*	% Po	% Cp	% Pn
1	#1	4.23	3.94	0.23	38.1	0.051	0.063	0.022	76.9	12.2	10.9
2	#1	4.17	3.35	0.24	38.2	0.043	0.060	0.026	78.4	12.2	9.4
3	#1	3.85	3.48	0.19	38.4	0.056	0.066	0.033	79.1	11.2	9.7
4	#1	3.28	3.28	?	38.5	0.037	0.043	0.018	81.3	9.6	9.1
5	#1	6.80	3.40	0.16	38.0	0.133	0.122	0.067	70.9	19.6	9.5
6	#1	4.07	3.82	0.19	38.3	0.051	0.064	0.032	77.6	11.9	10.5
7	#1	5.37	4.05	0.20	38.0	0.086	0.073	0.040	73.1	15.6	11.3
8	#2	4.50	3.16	0.21	38.1	0.086	0.157	0.036	78.4	12.9	8.7
9	#2	4.48	3.71	0.19	38.6	0.094	0.127	0.038	77.7	13.0	10.3
10	#2	4.28	3.35	0.16	38.2	0.095	0.145	0.050	78.3	12.4	9.3
11	#2	4.71	3.46	0.17	37.7	0.113	0.161	0.054	76.8	13.7	9.5
TOTAL MINE		4.63	3.66			0.074	0.085	0.036			

*Ounce per ton

**Block locations illustrated in Figure 16.4

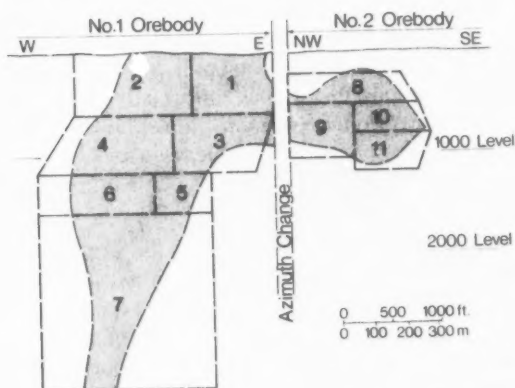


Figure 16.4. Little Stobie Mine—Generalized Longitudinal Section Showing Block Distribution Looking North.

Table 16.1 shows the distribution of the major ore metals and the calculated percentages of the 3 sulphide minerals. The data are derived from a computer analysis of 12 900 diamond-drill core samples weighted by sample length to produce average grades for specific blocks of mineralization. Most of the samples are from the Sublayer and the base of the quartz-rich norite. The data were adjusted to remove the effects of large rock inclusions and the unmineralized Main Mass norite. Values were normalized to 100% sulphide to facilitate comparison between blocks. All 11 blocks were studied to determine whether there was any correlation between metals. Apart from the Co:Ni ratio of 0.05:1, no statistically significant relationship was found.

Figure 16.4 shows the distribution of the blocks represented in Table 16.1 on a generalized longitudinal section of the mine. Blocks 1, 3, 5, and 7 represent the thickest, more highly mineralized part of the Number 1 orebody, whereas Blocks 2, 4, and 6 represent the weaker mineralization in the western half of the Number 1 orebody. The No. 2 orebody has been split into

the part closest to the Number 1 orebody (Block 9) and the upper, middle, and lower distal parts (Blocks 8, 10, and 11, respectively).

The 3 sulphide minerals, pyrrhotite, pentlandite, and chalcopyrite, are unevenly distributed throughout the deposit on a sample to sample basis, whereas the distribution appears more uniform when generalized as in Table 16.1. Pyrrhotite is ubiquitous, usually comprising 75 to 80% of all sulphide mineralization and characteristically containing variable amounts of pentlandite. Both the monoclinic and hexagonal forms of pyrrhotite are present with the pure monoclinic variety amounting to 95% of the total. The hexagonal, or non-magnetic variety, has only been found as a mixture (distinct mineral grains or exsolution laminae) with the monoclinic variety; it forms about 20% of the mixture as determined by X-ray diffraction methods. Limited sampling data indicate that the majority of the hexagonal pyrrhotite occurs along the base of the Number 2 orebody.

Pentlandite is always associated with pyrrhotite at Little Stobie. It is seldom visible to the naked eye but occurs as fine exsolution laminae within and around the pyrrhotite grains. It is the primary source of nickel at the mine. Pyrrhotite to pentlandite ratios vary widely throughout the mine on a sample to sample basis.

Chalcopyrite, like pyrrhotite, is ubiquitous. It is found as stringers, veins, and disseminations within the Sublayer and in all ore types. It can occur as massive sulphide and is particularly abundant in the footwall stringers. Copper to nickel ratios vary greatly throughout the deposit, but there is a tendency for concentrations of chalcopyrite to occur near the Footwall of the Number 1 orebody, and for the percentage of chalcopyrite in the sulphide to increase progressively with increasing depth into the footwall. In the Number 2 orebody, there is no apparent zonation of chalcopyrite.

The metal distribution is indicated in Table 16.1. Normalized nickel and cobalt values are fairly constant from one area to another, and cobalt particularly shows a strong correlation with nickel from block to block.

Copper and precious metals distributions are not uniform. In the Number 1 orebody above the 1200-foot level (Blocks 1 to 4), copper is marginally depleted, and the precious metals are depleted with respect to the total mine average. It is thought that this area may have been the source of the metal now found in the Number 2 orebody. Block 5 is enriched, but the values in this block are strongly influenced by a small, footwall-type orebody at the 1400-foot level. The large zone represented by Block 7 is enriched in copper and precious metals with respect to the mine average. This zone, because it was relatively undisturbed by post-ore events, may represent the original sulphide composition at Little Stobie.

The Number 2 orebody (Blocks 8 to 11, inclusive) is enriched in precious metals with respect to the total mine. Hoffman *et al.* (1979) found that the concentration of precious metals in the Number 2 orebody is twice that of the Number 1 orebody. Their findings are verified to some extent by the data presented in Table 16.1. If the Number 2 orebody is compared only with the upper (above 1200 Level) part of the Number 1 orebody, it will be seen that the former has been enriched in precious metals by a factor of 3. However, if the Number 2 orebody and the Number 1 orebody above 1200 Level are combined and are compared to the Number 1 orebody below 1200 Level, there is no significant difference in precious metal values. This indicates that the Number 2 orebody was originally part of the upper part of the Number 1 orebody.

The other apparent zoning in the Number 2 orebody is an enrichment in precious metals toward both the distal and lower parts of the Number 2 ore zone.

Structure

Two post-ore fault systems are present, striking N45°W and N60°W and dipping 80°W to 80°E and 0° to 40°E, respectively. These faults tend to pinch and swell, ranging from 1 cm to 3 m in width with frequent horse tails and interbraided features. Schist, mud, and fault gouge with occasional calcite, quartz, marcasite, mountain leather, and vugs are found along these structures. In the vicinity of the ore, chalcopyrite and pyrrhotite have been carried along the faults for a distance of 3 m into the footwall. The faults cut all rock and ore types within the mine environment and displace rock units from 0 to 10 m. Where major ore-rock contacts are intersected, the faults tend to follow the contact for up to 100 m, giving the erroneous impression that the ore is controlled by contact shearing. The minor amounts of contorted schist inclusion sulphide at Little Stobie are associated with these structures.

DISCUSSION

The Little Stobie deposit is similar to other contact deposits on the South Range. It occupies an embayment at the base of the Sudbury Igneous Complex, has a quartz-rich norite hanging wall, has all of the common Sudbury ore types, contains within the Sublayer the normal sequence of progressively increasing sulphide content from the hanging wall to the footwall, and has experienced post-ore shearing. It differs from the typical South Range deposit in that above the 1200-foot level the ore sequences are mixed and the metal distribution is not uniform throughout. The sequence of events resulting in the Little Stobie deposit is perceived to be as follows.

1. The Sudbury Event was accompanied by general Sudbury brecciation of the Footwall and more intensive brecciation of the contact between the Number 2 orebody granite and the adjacent massive, fine-grained "greenstone". Sudbury Breccia preferentially forming along rock contacts, leaving the main body of the rock unit relatively unbrecciated, is a common phenomenon at Sudbury. It is particularly apparent where the main rock body is a homogeneous, uniform unit such as granite or a thick, extensive volcanic flow.
2. Introduction of the Sublayer into the Little Stobie embayment, followed by gravitational settling of the sulphides to form the various ore types of the Number 1 orebody, with concentration of the ore within the deepest part of the Little Stobie embayment and the penetration of the Footwall by copper-rich stringers, gave rise to the standard suite of ore types which typifies South Range contact deposits.
3. Introduction of the norite above the Sublayer.
4. A readjustment of the Footwall while the Sublayer was still in a viscous state, possibly as a result of major slumping, injection of the norite, or reaction to late stages of the Penokean deformation. This Footwall readjustment compressed the Sublayer and weakened or made permeable the breccia zone of the Number 2 orebody. Under this compression, the Sublayer flowed into the breccia zone. The granite contact, which is east of the deepest part of the Little Stobie Embayment, was at that time in contact with weakly mineralized Sublayer. Consequently, the first material drawn off was low grade disseminated material which moved into the breccia zone, incorporated the breccia matrix, and cooled rapidly. This produced the elongated sulphide blebs, flowage lines, and elliptical inclusions of the upper part of the Number 2 orebody. Most of the breccia matrix remained on the margins of the ore zone, forming a sheath around the orebody with some of the matrix material picking up sulphide as blebs and fragments. As material continued to be squeezed into the fractures, the source of the ore

zone now became the deeper and higher grade sections of the Number 1 orebody above the 1200-foot level. This higher grade mineralization was emplaced below the blebby disseminated ore and cooled more slowly because of the retained heat from the earlier mineralization. The precious metals being the most mobile fraction had time to migrate to the distal and lower part of the Number 2 orebody. This may be analogous on a smaller scale to the upside-down zoning described at the Frood Mine (Zurbrigg 1957; Hawley 1965).

4. The overall movements and the reduction of Sublayer volume caused major mixing within the remainder of the Number 1 orebody Sublayer. Viscous and partly solidified material were mixed, resulting in conflicting age relationships between the ore types, although some of the typical contact deposit zonation was preserved. Most of the massive sulphide was protected from this adjustment because it was buried within the deepest part of the embayment. The ubiquitous gabbro peridotite inclusion sulphide incorporated blocks of ragged disseminated sulphide and interstitial sulphide with clearly defined boundaries, but in other parts of the deposit the gradational boundaries were preserved. The Number 2 orebody breccia zone was now full of Sublayer so that Main Mass norite inclusions were not drawn any farther than the "cross-over" area.
5. At this stage, the area stabilized allowing all units to cool and crystallize. After consolidation, later cross faulting intersected and locally disrupted the ore and associated rocks.

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Inco Limited has given permission to publish the paper.

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CHAPTER 17

Falconbridge and East Mines

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ABSTRACT

Falconbridge and East Mine ore deposits occur within fault zones between the base of the Sudbury Igneous Complex and metavolcanic-metasedimentary rocks of the Stobie Formation. Contorted schist inclusion sulphides within the shear zones are referred to as the Main Zone, and inclusion massive sulphides occurring as discontinuous lenses within metavolcanic rocks are referred to as Southwall ore zones. The latter are structurally related to major tangential shears to the Main Zone fault. The Main Zone dips steeply north in the upper levels and steeply south in the lower levels of the mines. Pre-ore silicification of footwall rocks and extensive quartz-carbonate veining are indicative of early hydrothermal activity. Highly altered Sublayer, marginal to the Complex, is considered to be the magmatic source for the sulphide mineralization. As a whole, the deposits are depleted in Cu, Pt, Pd, and Au when compared to other Sudbury deposits. Fractional crystallization of a sulphide melt can account for this anomaly. Gouge-filled post-ore faults along the Main Zone are considered to be the most likely mechanism for removal of the Cu and precious metal enriched fraction. Late cross fractures throughout the deposits are filled with sphalerite, galena, marcasite, and carbonates.

INTRODUCTION

The Falconbridge Mine and East Mine ore deposits occur at the southeastern margin of the Sudbury Igneous Complex in Falconbridge Township. The Falconbridge deposit was discovered by Thomas Edison in 1899 using a combined magnetic and electrical geophysical survey of his own design. In 1916, the Longyear Company partially outlined the orebody by diamond drilling, and subsequently sold the property to Ventures Limited in 1928. The mine was brought into production in 1929 under the direction of Falconbridge Nickel Mines Limited (now Falconbridge Limited). When mined out, the mine will have produced approximately 36 million tonnes of ore.

The East deposit was also indicated by surface drilling in 1916 by the Longyear Company and was subsequently explored by drifts driven from Falconbridge Mine. A shaft was sunk and production started in 1951.

GENERAL GEOLOGY

Earlier descriptions of the Falconbridge and East Mine deposits are those of Davidson (1948) and Lochhead (1955). The ore zones occur within 2 east-striking shear zones between the base of the Sudbury Igneous Complex and the metavolcanic-metasedimentary rocks

of the Stobie Formation. The 2 orebodies are in effect, sheets of sulphides occurring within these shear zones, which are coincident with the norite-metavolcanic rock contact. They are separated by 600 m of unmineralized contact. The sulphides within the shear zones are referred to as "Main Zone" contorted schist inclusion sulphides, which at Falconbridge Mine extend for approximately 2000 m on surface and to 1800 m in depth. The Main Zone at East Mine is approximately 900 m in length on surface and at least 1950 m in depth. A second ore type is referred to as "Southwall" inclusion massive sulphides which occurs as discontinuous lenses within metavolcanic rocks between the 1200 and 5500 levels of the Falconbridge Mine.

The Falconbridge Main Zone dips steeply north in the upper levels, is vertical near the 1200 level, and dips steeply south in the deepest levels. Below the 6050 level, the contact flattens to approximately 65°S, the shear zone becomes tight, and the sulphide-rich zone narrows to <15 cm in width. The orebody plunges vertically in the upper levels and rakes slightly to the east at lower levels. The ore zone pinches and swells, and is variable in thickness from a few cm to 50 m, with an average width of about 5 m.

The East Main Zone dips steeply north to vertical in the upper levels and vertical to 70°S in the middle and lower levels. It is vertically plunging with a slight rake to the west in the lower levels. This ore zone varies in width from a few cm to 28 m with an average of about 5 m.

Rock Types

Figure 17.1 illustrates the geology at surface and on the 4025 level of the Falconbridge Mine. South Range norite, constituting the Lower Zone of the Sudbury Igneous Complex, occurs immediately north of the Falconbridge and East Mine orebodies. With an increasing quartz content, the norite grades into quartz-rich norite, a basal unit of the Complex (Naldrett *et al.* 1970). Strongly altered Sublayer occurs in places south of the norite contact, commonly adjacent to Southwall ore zones.

The Stobie Formation is present south of the Falconbridge and East Mine orebodies. The original rocks were basaltic to andesitic flows with intercalated pyroclastic rocks, and arenaceous to argillaceous sedimentary rocks. All have been metamorphosed under greenschist facies conditions and are now collectively termed "greenstone". These rocks are green to dark green in colour, fine to coarse grained, schistose to massive, and either equigranular, porphyroblastic, or amygdaloidal.

Where silicification is prevalent, the term jasperoid is used locally (Davidson 1948). Jasperoid is yellowish grey to greyish blue in colour and fine to medium grained. It is a compact quartz-rich rock, al-

most all of which occurs south of the contact in the "greenstone", and is frequently associated with Southwall orebodies. It appears that at least in part, the jasperoid originated from thermal recrystallization of arenaceous sedimentary rocks and in part from remobilized quartz and the resulting silicification of adjacent volcanic rocks.

Ore Types

The "Main Zone" contorted schist inclusion sulphide is a sulphide breccia composed of pyrrhotite, pentlandite, and chalcopyrite, and enclosing fragments of hanging wall norite in the upper levels and hanging wall "greenstone" in the lower levels. The Main Zone contains 30 to 80% subangular to rounded inclusions, varying in size from < 1 mm to > 1 m in diameter. Narrow sections or pinches in the ore zone appear to be controlled by subparallel faulting. Thicker zones or swells are controlled by tangential shears in norite or by complex faulting under Number 1 Flat Fault. Figure 17.2 illustrates the relationship of these structures to ore widths.

"Southwall" inclusion massive sulphide zones occur south of the Main Zone and contain up to 30% inclusions composed of "greenstone", quartz, and jasperoid. The Southwall sulphides are coarser grained than Main Zone sulphides and contain abundant euhedral pentlandite crystals up to 3 cm in diameter. Typical Southwall orebodies are tabular-shaped lenses occurring at or near the contact with the Main Zone. These lenses vary from a few cm to 36 m in width and extend up to 60 m south of the Main Zone. The location of lenses is structurally related to tangential shears in "greenstone" below the 1200 level. Shears occur where there is a change in dip or strike of the Main Fault, resulting in discontinuous sulphide lenses of above average pentlandite and chalcopyrite content. Figure 17.2 illustrates the location of massive Southwall sulphide lenses relative to the Main Zone sul-

phides. It is evident from Figure 17.3 that a change in strike of the Main Fault near Section 149E, a tangential shear branching to the east, another tangential shear near Section 154E striking southwest, and a Number 2 type fault striking southeast, all have a controlling influence on sulphide deposition, in a complex structural pattern.

STRUCTURE

In view of the importance of structural elements to ore location, the major features will be described in more detail. Figure 17.4 is a longitudinal projection of the Falconbridge Mine, looking north, on which the major faults have been projected.

Main Fault

The most prominent structural feature is the Main Fault, which at surface is in contact with the Main Zone orebody for a strike length of 2000 m along the norite-"greenstone" contact. Wall rocks to the fault are strongly foliated and brecciated, and fault gouge attains widths of up to 1 m at about the centre of the orebody, but averages 15 cm throughout.

West of the ore zone, the norite contact strikes to the southwest, but the Main Fault continues westward within unmineralized norite. The contact here is not sheared or faulted and no economic concentrations of sulphides are present. To the east, the Main Fault strikes southeastward into the "greenstone" with no associated mineralization. The norite contact east of Falconbridge Mine is cross faulted but not sheared. It is barren of sulphides for a strike length of nearly 600 m, before a subsidiary fault to the Main Fault, which strikes slightly south of east in norite, becomes coincident with the east-striking contact. This fault follows the contact for approximately 1000 m and is the locus for ore deposition at the East Mine. The resulting ore zone is quite similar in most details to the Falconbridge orebody.

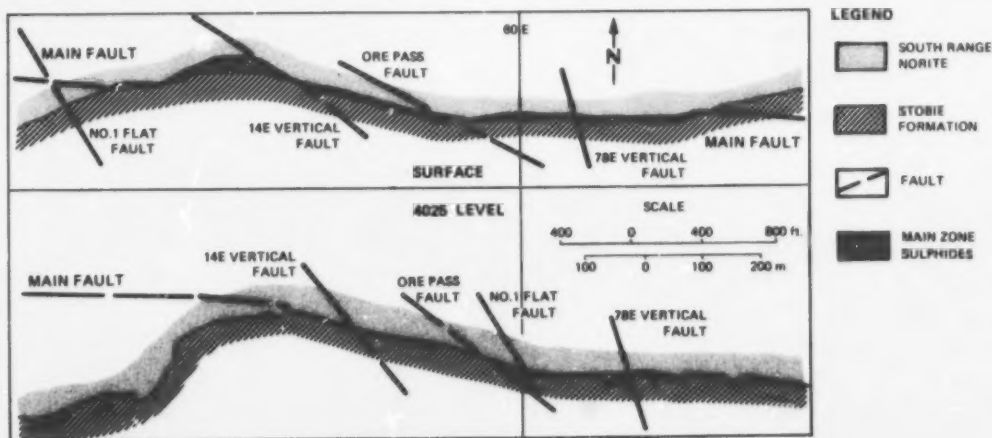


Figure 17.1. Geological plan, surface and 4025 Level, Falconbridge Mine.

South Fault

The South Fault is in contact with the Main Zone to the north, and "greenstone" or Southwall massive sulphides to the south (Figures 17.2 and 17.5). The Main Zone forms a wedge of ore bounded by Number 1 Flat Fault to the east, the Main Fault to the north, and the South Fault to the south. This structure controls the wide zone of sulphides under the Number 1 Flat Fault. The South Fault joins the Main Fault west of the sulphide wedge. This point of intersection is shown in Figure 17.4 and can be seen under Number 1 Flat Fault in the middle parts of the mine. It can be traced from just below the 2100 level, under Number 1 Flat Fault, to just below the 4350 level. For most of this length, the orebody attains widths of over 10 m, and the fault gouge widths up to 0.5 m.

Tangential Shears

Tangential shears to the Main Fault favour the hanging wall or norite side above the 1200 level. Below this ho-

rizon, the Main Fault is overturned to the south and the shears again favour the hanging wall, which is "greenstone" at this point.

Section 5E (Figure 17.6), from the surface to the 1200 level at the Falconbridge Mine, illustrates the Main Fault dipping steeply north to vertical with a norite hanging wall. Tangential shears branch from the Main Fault and produce swells in the Main Zone. The contact of sulphides and norite is abrupt, and the norite is devoid of sulphides. Figure 17.6 also shows Section 20.5E from 2450 level to 3500 level and illustrates the Main Fault dipping south with a "greenstone" hanging wall. Tangential shears branch from the fault, enter the "greenstones", and form the locus for Southwall ore zones.

Number 2 Fault is the most continuous of a set of tangential shears which have an average strike of $S40^{\circ}E$ and dip 70° to 75° southwest. Most sets occur below the 4025 level and below the Number 1 Flat Fault. These shears are through-going structures and can be traced in both norite and "greenstone".

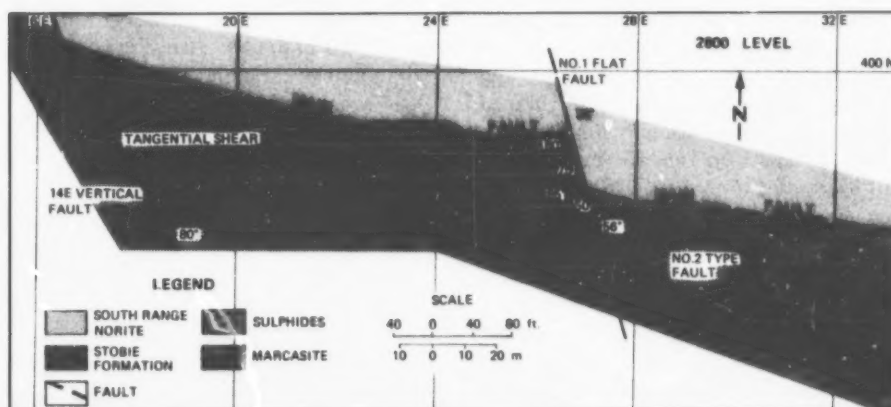


Figure 17.2. Geological plan, 2800 Level, showing relationship of the Main Zone and Southwall orebodies to principal structural features, Falconbridge Mine.

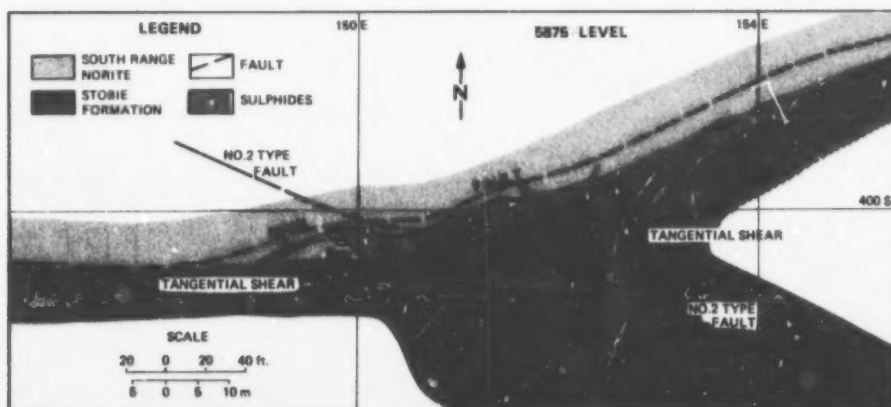


Figure 17.3. Structural pattern of the Main Fault and Tangential Shears controlling sulphide location on the 5875 Level, East Mine.

Number 1 Flat Fault

The Number 1 Flat Fault is right lateral, strikes S30°E and dips 45° northeast. The trace of the fault throughout the Falconbridge Mine is shown in Figure 17.4, but it continues to the east and intersects the East Mine workings on the 6050 level. Fault gouge in the Number 1 Flat Fault varies in width from a few cm to 0.5 m. No sulphides are associated with this structure.

14E and 78E Vertical Faults

There are numerous post-ore fractures containing late stage mineralization consisting of marcasite, carbonate, galena, and sphalerite. Two major, through-going structures, the 14E and 78E Vertical Faults, are illustrated in Figure 17.4. Secondary marcasite extends up to 90 m horizontally from the 78E Vertical Fault, and from the upper levels down to the 5875 level (Figure 17.8). The 14E Vertical Fault is right lateral, strikes S35°E and dips 80° ± 5° northeast. The 78E Vertical Fault is left lateral with S15°E strike and 80° dip to the east.

Number 1 Ore Pass Fault

There are a series of parallel faults striking S65°E and dipping 85° south, the most prominent being the Number 1 Ore Pass Fault (Figures 17.4 and 17.5). This fault, in proximity to the norite-“greenstone” contact,

changes strike and is coincident with the contact for a short distance before cutting the Main Zone and continuing into the opposite wall rocks. Numerous microseismic disturbances are associated with the Number 1 Ore Pass Fault and associated structures in the deeper levels of the mine.

SULPHIDE MINERALIZATION

The predominant sulphide is pyrrhotite, which tends to be coarser grained adjacent to the Number 1 Flat Fault and finer grained at the limits of the deposit. The majority of the pyrrhotite is monoclinic, but there is a slight increase in the content of hexagonal pyrrhotite in the lower levels of the East Mine. The Ni content of pyrrhotite varies between 0.29 and 1.18 wt% and averages 0.63 wt%. The higher Ni contents are generally associated with cross fractures and swells in the Main Zone, in combination with adjacent wallrock shearing in the upper levels. Higher Ni concentrations in the lower levels are associated with the Number 1 Flat Fault, where extreme fracturing and shearing occurs in the Main Zone. Lower nickel contents are associated with very fine grained, dark breccia sulphides, most of which occur at or near the limits of the Main Zone, where the sulphides are confined to a tight fault contact. The pentlandite to pyrrhotite ratio increases with depth and with distance to the south.

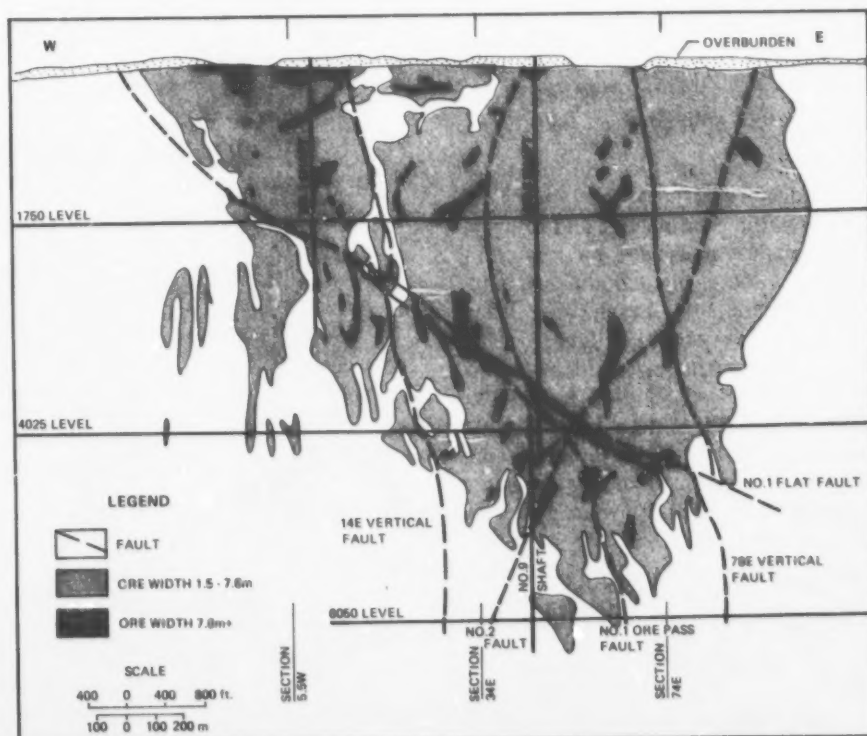


Figure 17.4. Longitudinal projection, Falconbridge Mine, in the plane of the Main Fault.



Figure 17.5. Geological plan, 4025 Level, Falconbridge Mine, showing wide sulphide zone confined by the Main Fault, Number 1 Flat Fault, and the South Fault.

Pentlandite is more abundant and better developed in the Southwall lenses, where euhedral crystals may reach 3 cm in diameter. Cobalt is randomly distributed in the upper levels, but its content in pentlandite increases in the lower levels. Platinum group elements are present in gersdorffite, chalcopyrite, and pentlandite.

Chalcopyrite occurs as stringers and blebs within the Main Zone and as veins at the limits of the Southwall lenses, or adjacent to large inclusions within these lenses. Gold and silver occurs mainly in solid solution in chalcopyrite.

Gersdorffite crystallized early and has been extensively replaced by later sulphides. Although 70% of the gersdorffite occurs in Southwall lenses, it accounts for < 1% of the total sulphides.

Both primary and secondary marcasite are present in the Falconbridge orebody. Primary marcasite occurs as late fracture fillings or in vugs, and contains little, if any Ni. Secondary marcasite occurs within both the Main Zone and Southwall orebodies and is associated with zones of later faulting and shearing. It has a drusy appearance and is very friable. Figure 17.8 illustrates the extent of secondary marcasite alteration in the Main Zone and Southwall sulphides adjacent to a late fault, designated the 78E Vertical Fault. The alteration extends as far as 90 m from the fault. Numerous late fractures containing secondary marcasite, carbonates, galena, and sphalerite are present throughout the orebodies.

Metal concentrations in the Falconbridge deposit determined by Naldrett *et al.* (1982) are reproduced here as Table 17.1. Absolute values for 23 samples, widely separated throughout the deposit, have been recalculated to reflect the concentration of metal in the sulphide phase and averaged. Of interest is the Cu/Cu + Ni ratio of 0.22 which is low compared to other Sudbury deposits. The distribution of platinum group

elements is also unusual in the Falconbridge deposit. Levels of Os, Ir, Ru, and Rh are very similar to the richest reported for Sudbury ores while the concentrations of Pt and Pd are very much lower. These results led Naldrett *et al.* (1982) to speculate that a Cu, Pt, and Pd enriched part of the original deposit has been removed by post-ore faulting.

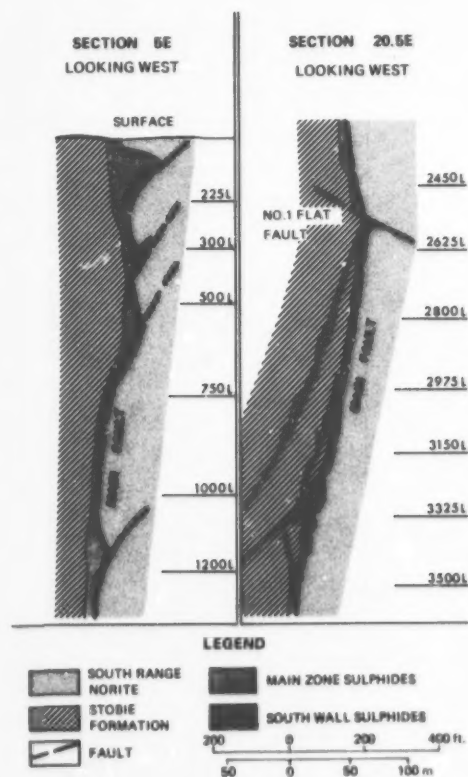


Figure 17.6. Vertical cross-sections 5E and 20.5E, Falconbridge Mine, illustrating changing dip of the Main Fault zone and control of Southwall ore zones by Tangential Shears.

TABLE 17.1: CONCENTRATION OF METALS IN FALCONBRIDGE DEPOSIT.*

Ni	Cu Wt %	Co	Pt	Pd	Rh	Ru ppb	Ir	Os	Au
5.35	1.52	0.22	546	381	287	225	144	40	174
Cu/Cu + Ni = 0.22			Pt/Pt + Pd = 0.0589			Pt + Pd/Ru + Ir + Os = 2.27			

*No. of samples 23. Recalculated values to reflect concentration in 100% sulfide. Data from Naldrett et al. (1982)

DISCUSSION

The Falconbridge and East Mines are fault controlled deposits at the southeastern corner of the Sudbury Igneous Complex. It has been suggested by Lochhead (1955) that the fault zones containing the mineralization were pre-Sudbury Igneous Complex in age and that they governed the position of the outer edge of the norite in Falconbridge Township. Subsequent to consolidation of the Complex, reactivation of the faults along the norite-“greenstone” contact resulted in an intensely schisted and brecciated zone. Initially, this zone served as a conduit for hydrothermal fluids, which caused extensive silicification and quartz-carbonate veining of the brecciated zone and adjacent

rocks. Further fault movements prior to the introduction of sulphide mineralization are indicated by the presence in the ore of numerous inclusions of norite and “greenstone” displaying varying degrees of schistosity and silicification and of quartz-carbonate vein material.

This is appreciable evidence of metal zonation in the Falconbridge deposit. The Ni content increases with depth and with distance into the “greenstone” hanging wall, and copper also shows a tendency to increase in the hanging wall ore shoots. Early arsenides in the ore zone are unquestionably partly replaced by later sulphides. As Naldrett *et al.* (1982) have observed, the Pt, Pd, and Au depletion in the deposit is coupled with a much lower Cu and somewhat higher

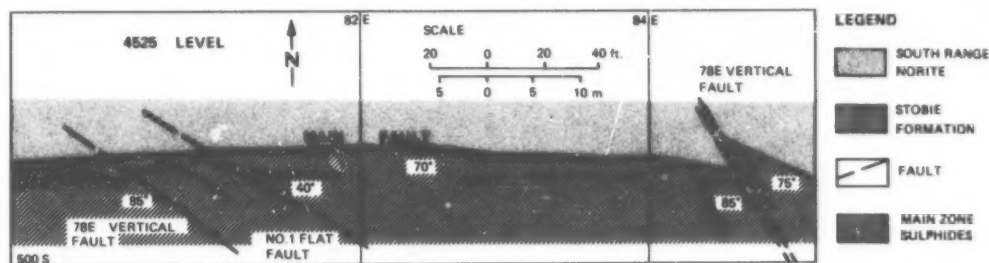


Figure 17.7. Geological plan, 4525 Level, Falconbridge Mine, illustrating sulphide location in relation to the Main Fault, Number 1 Flat Fault, and 78E Vertical Fault.

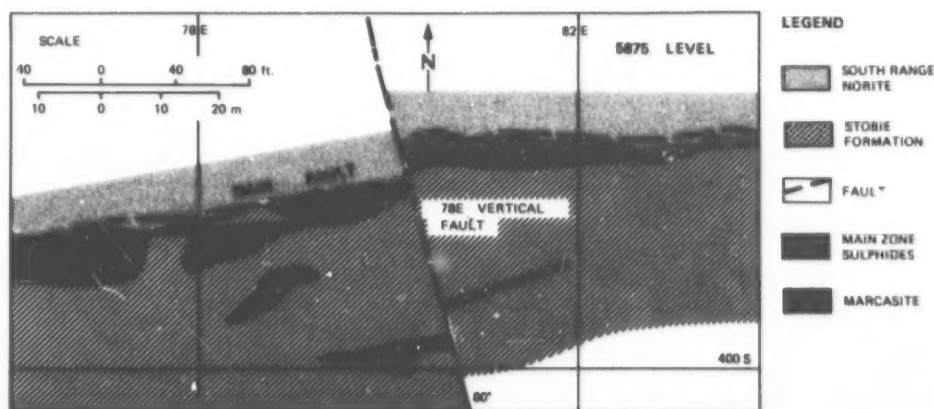


Figure 17.8. Geological plan, 5875 Level, Falconbridge Mine, showing marcasite distribution in relation to the 78E Vertical Fault.

Co content than typical for Sudbury ores. There is no apparent progressive variation in the $(Pt + Pd)/(Ru + Ir + Os)$ ratio within the Main Zone, although sampling covered a 1600 m vertical interval. As a whole, the Falconbridge and East Mine ore deposits are compositionally similar to the Hangingwall Zone at Strathcona, where fractional crystallization of a sulphide melt produced Cu, Ni, Pt, Pd, and Au enrichment in the ores at greater distances from the Sublayer magmatic source. If this process was operational at Falconbridge, a significant quantity of Cu, Pt, Pd, and Au enriched differentiated ores are absent. Tectonic removal of this material by post-ore faulting is a distinct possibility. Gouge-filled faults, indicative of late movement are an obvious feature of the Main Zone.

Throughout the ore deposits, there are numerous late cross fractures that are generally filled with sphalerite, galena, marcasite, and carbonates. In addition to this late stage mineralization, supergene alteration of the ore assemblage to Ni-bearing marcasite occurs adjacent to 2 late, but prominent vertical faults.

ACKNOWLEDGMENTS

Many individuals from Falconbridge Sudbury Operations have contributed to our knowledge of these de-

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GEOPHYSICS

CHAPTER 18

Gravity and Magnetic Characteristics of the Sudbury Structure

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MAP

Map NL-16/17-AM Sudbury, Geological Survey of Canada. Coloured magnetic map. Scale 1:1 000 000.

CHARTS

Chart A Bouguer gravity map. Scale 1:1 000 000.

Chart C Bouguer gravity and generalized geological map of the Sudbury area. Scale 1 : 250 000.

ABSTRACT

The Sudbury Structure occurs within an elliptical gravity high of +30 mgal that forms part of a chain of positive gravity anomalies extending for more than 350 km along an arc from Elliot Lake to Englehart. The double peaked gravity anomaly is much broader than the Sudbury Structure. Based upon the measured densities of surface rock samples, it is concluded that the gravity anomaly cannot possibly be caused by a subsurface development of the Sudbury Igneous Complex. The anomaly must be due to denser rocks which are not seen at the surface, except possibly as inclusions within the Sublayer. From gravity observations, the hidden mass is calculated to be sill-like in form and subhorizontal in attitude, at a depth of 5 to 8 km, and about 3 to 4 km in maximum thickness. Its average density is calculated to be in the range of 3.0 to

3.3 g/cm³, which suggests a mineralogy resembling anorthosite gabbro, olivine gabbro, or dunite.

The hidden structure appears to divide into 2 parts. The southern part contains the bulk of the mass, and appears to be essentially flat-lying, at a depth of about 6 to 8 km. It is non-magnetic, and may therefore be made up largely of magnesium-rich rocks. The northern part appears to be smaller and shallower (2 to 5 km), with a moderate southward dip. It is associated with a large magnetic anomaly which implies a concentration of 5 to 10% by volume of magnetite throughout the volume of dense material. The combination of high density and high apparent magnetic susceptibility (approximately 0.25 SI units) suggests that the northern part of the hidden structure may consist of partly serpentinized mafic/ultramafic rocks. The position of the hidden mass indicates that it is probably

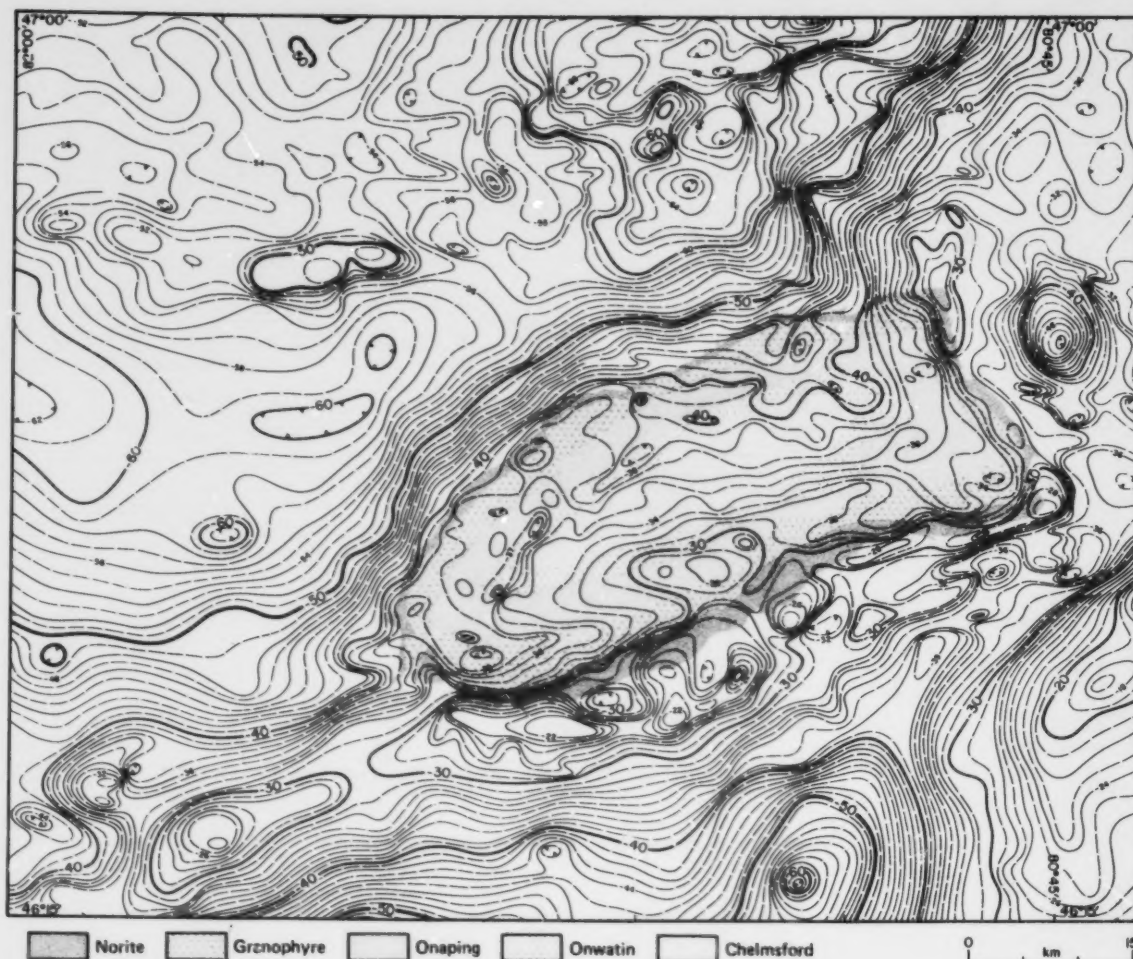


Figure 18.1. Bouguer gravity map, Sudbury area. Contour interval is 1 mgal.

older than the Sudbury Structure. In terms of its volume, depth, and density, it is similar to other layered gabbroic intrusions such as the Muskox and Duluth Complexes. Geophysics does not make clear what relationship, if any, it might have with the Sudbury Igneous Complex.

INTRODUCTION

The Sudbury Structure occurs within a large, elliptical gravity high of about +30 mgal (+300 g.u.) that is part of a chain of positive gravity anomalies extending over a distance of nearly 350 km from the Elliot Lake area through Sudbury and Lake Temagami to Englehart (see zone ELE in Figure 2.6 of Card *et al.*, this volume). The surface exposure of the Sudbury Structure does not lie at the centre of the gravity anomaly (see Figure 18.1, Charts A and C); rather, its axis is offset to the north of the gravity axis by about 8 to 10 km. The gravity anomaly is much broader than the Sudbury Structure and extends well beyond its boundaries. The

Sudbury Structure is also associated with a distinctive, elliptical, positive magnetic anomaly (Figure 18.2). Like the gravity anomaly, the magnetic anomaly is broader than the Sudbury Structure and the axis of the Structure is offset to the South of the magnetic axis.

The mafic rocks of the Sudbury Igneous Complex, and in particular the Lower Zone norite, have an average density that exceeds that of the surrounding gneissic rocks by not more than 0.1 g/cm^3 . To produce an anomaly of +30 mgal, the mafic rocks (Lower Zone) of the Sudbury Igneous Complex would have to be in excess of 10 km thick. The greatest thickness seen in outcrop is 2 km. Even if thicknesses as great as 10

¹The unit of density that is used in this article is g/cm^3 . The SI unit of density is kg/m^3 . Thus, a density of 2.74 g/cm^3 , given in SI units, would be written either as 2740 kg/m^3 or as $2.74 \times 10^3 \text{ kg/m}^3$. A conventional unit for density in the new International System has not yet been established.



Figure 18.2. Total-field aeromagnetic contours. Profile locations are also shown.

km were to exist at depth, it is doubtful that they could produce the observed gravity gradients. It seems unlikely, therefore, that the gravity anomaly has its origin in a downward extension of any of the rocks that are known to exist within the Sudbury Structure. Denser rocks than these are needed in order to account for the amplitude and horizontal gradient of this gravity feature.

In a few places around the rim of the Sudbury Igneous Complex, anorthositic gabbros have pierced the Footwall rocks (*see* Map 2491, back pocket). According to the measured densities, these are significantly more dense than the rocks of the Sudbury Igneous Complex. Their presence within the Footwall indicates that they may also exist at depth. There are some relatively high-density mafic rocks within the Levack Gneiss Complex, but judging from surface exposures, their total volume is small and hence their gravity effect is probably also small (about 1 to 2 mgal). No other rocks exist anywhere at surface which have a sufficiently high density to produce gravity effects of such significant size. Accordingly, based upon the rocks

mapped in and around the Sudbury Structure, a large, buried mafic or ultramafic mass or masses would appear to offer the most plausible explanation for the Sudbury gravity and magnetic anomalies.

GRAVITY SURVEYS AND PREVIOUS INTERPRETATIONS

A regional gravity survey in the Sudbury area was reported by Miller and Innes (1955), who carried out an early quantitative interpretation to explain the Sudbury gravity anomaly. A detailed gravity survey was carried out in 1970 by the Earth Physics Branch of the Department of Energy, Mines and Resources, Canada (Popelar 1971). During later surveys by the Ontario Geological Survey, many additional gravity stations were established in the region north and east of Sudbury (Gupta 1981).

An interpretation of the Earth Physics Branch gravity data was carried out by Popelar (1972). He proposed 3 models for the Sudbury Structure to explain the gravity anomaly.

The first model (Model I) was an asymmetrical, funnel-shaped body of norite and norite-gabbro (density 2.83 g/cm^3) having a maximum depth extent of about 20 km, which is embedded in a light, granitic crust having an average density of 2.63 g/cm^3 . The funnel contains granophyre (density 2.68 g/cm^3) to a depth of 9 km overlain by Whitewater Group sedimentary rocks (density 2.63 to 2.73 g/cm^3) to a depth of 3 km. The gravity anomaly that is produced by this configuration has approximately the same amplitude as the Sudbury anomaly, but it is much narrower. Popelar concluded that no funnel-shaped model of the Sudbury Structure, even allowing the most extreme depth, could account for the shape of the Sudbury anomaly.

Popelar's second model (Model II) resembles a folded sill or lopolith of norite asymmetrically folded to the south, which rests upon a gneissic substratum (density 2.73 g/cm^3) and is overlain by more or less conformable layers of granophyre and Whitewater Group sedimentary rocks. The thickness of the norite is about 3.5 km and its maximum depth of burial is 5 km, while the granophyre has a maximum thickness of about 4 km. This model produces a gravity effect which more closely resembles the Sudbury gravity anomaly in shape. The model again is too narrow, and is much too low in amplitude owing to the small density difference between the norite and its substratum.

The third model presented by Popelar (Model III) combines the folded sill hypothesis with the concept of a light, granitic substratum having a low background density (2.65 g/cm^3). Popelar was able, after some refinements, to shape this model into a form whose gravity effect matches the Sudbury anomaly reasonably well. The essential features of this density model are:

1. a folded sill of norite-gabbro (density 2.83 g/cm^3) approximately 4 to 5 km thick, which is overturned to the south so that it protrudes beyond the borders of the Sudbury Igneous Complex
2. a thin layer of gneiss, 1 to 2 km thick (density 2.73 g/cm^3), beneath the norite
3. a substratum or crust beneath the gneiss that is made up largely of light granitic material, of density 2.65 g/cm^3 , that extends to a depth of at least 15 km

The norite has a maximum depth of burial of about 4.5 km, and is overlain by approximately 2.5 km of granophyre and 2 km of Whitewater Group rocks. It is noteworthy that the folded norite sill hypothesis was finally chosen by Popelar in preference to a funnel-shaped body.

Popelar's density Model III poses a number of serious problems. For instance, the postulated thickness of the norite (approximately 5 km) is much greater than the observed thickness measured in outcrops. Of more critical importance than the thickness of the Sudbury Igneous Complex, however, are the difficulties in-

volved in assuming a substratum or crustal layer of granite (density 2.65 g/cm^3) at least 15 km thick beneath the Sudbury Structure. If the crust beneath the Sudbury Structure was to contain 15 km of granite having this density, the Bouguer gravity field would be unusually low in the Sudbury region, which is not the case. According to Popelar (1972), the gneissic rocks have an average density of 2.73 g/cm^3 . The density contrast with the norite (0.1 g/cm^3) is insufficient to produce the observed gravity effect, so that in order to preserve the folded sill model of the Sudbury Igneous Complex, Popelar is forced to assume that the gneiss exists only as a thin (1 to 2 km) layer overlying a lighter (2.65 g/cm^3) granitic crust which is shown as extending southward beyond the Grenville Front Tectonic Zone (see Popelar 1972, Figure 8b).

We cannot accept Popelar's hypothesis of a lighter and probably younger², dominantly granitic crust overlain by a thin layer of denser and older gneiss. Such a configuration, besides being improbable, would be gravitationally unstable. Moreover, if the regional background density was approximately 2.65 g/cm^3 as Model III suggests, then granitic plutons of similar density would not produce gravity anomalies. However, granite bodies in the Sudbury region without exception, give rise to negative gravity anomalies, implying that the crustal rocks must be more dense than the granites. Numerous authors, including Garland (1965), Gibb (1968), Goodwin and Ridler (1970), Goodwin (1977), and Gupta and Grant (In Press) have made estimates of the average density of the Superior and Southern Province crust based upon its average composition and upon surface density measurements. All arrive at values that fall within the range 2.72 to 2.76 g/cm^3 . None has suggested an average density as low as 2.65 g/cm^3 . Models of the Archean crust in the general region (see Percival and Card 1983, for example) indicate that the dominant rock type in the upper 15 to 20 km is tonalitic gneiss with an average density of about 2.73 g/cm^3 . Finally, our own calculations based on a large number of density measurements demonstrate that the average background density in the region is about 2.73 g/cm^3 (see Table 18.1).

An attempt was made to reconcile Popelar's Model III with a conventional gneissic crust having an average density of 2.73 g/cm^3 , rather than a granitic crust having an average density of 2.65 g/cm^3 . However, this could only be achieved by assuming unreasonably high density values for the rocks of the Sudbury Structure. In fact, as Popelar has shown, there

²The U-Pb Zircon age for the youngest granite in the region is 2668 Ma (Krogh and Turek 1982); for the Creighton Pluton, it is 2333 ± 32 Ma (Frarey *et al.* 1982); and for the Murray Pluton, 2388 ± 20 Ma. The age of the gneissic rocks is 2711 ± 7 Ma (Krogh *et al.*, this volume).

CHAPTER 18

TABLE 18.1: CALCULATION OF REGIONAL, (BACKGROUND) MEAN DENSITY BASED ON AERIAL DISTRIBUTION OF ROCKS IN PARTS OF SOUTHERN, SUPERIOR, AND GRENVILLE PROVINCES (FROM GUPTA AND GRANT IN PRESS).

ROCK TYPE	AREA % (A)	MEAN DENSITY (ρ) g/cm ³	(A) x (ρ)
Granitoid, (Granite, Trondhjemite, Granodiorite, quartz-diorite, Granite gneiss)	33	2.72	0.8976
Metavolcanic rocks			
Felsic	2.0	2.72	0.0544
Mafic	7.5	2.92	0.219
Metasedimentary rocks			
Superior Province	1.0	2.72	0.0272
Southern Province (Huronian)	31.0	2.69	0.8339
Grenville Province	15.0	2.67	0.4005
Other Intrusive rocks	6.0	2.84	0.1704
Grenville Intrusive rocks	3.0	2.75	0.0825
Paleozoic Sedimentary rocks	1.5	2.67	0.0401
Weighted Mean Density = 2.73 g/cm ³			

is no shape for the norite that will account for the Sudbury gravity anomaly, if the density contrast is only +0.1 g/cm³.

Consequently, it was decided to test an alternative interpretation based on the assumption that the Sudbury gravity anomaly is caused by rocks at depth that are denser than the Sudbury Igneous Complex rocks.

GENERAL GEOLOGY

The Sudbury Structure is outlined by the Sudbury Igneous Complex, a composite mafic-felsic intrusion some 2 to 6 km in outcrop width that forms an elliptical ring approximately 60 km long and 27 km wide (Figure 18.1). Within this ring is a synclinal basin occupied by breccias, mudstones, and wackes of the Whitewater Group. The Onaping Formation at the base of the Whitewater Group consists of heterolithic lower breccias, is about 1800 m thick, and is overlain by the Onwatin Formation, a carbonaceous and pyritic mudstone some 300 m thick which in turn is overlain by the Chelmsford Formation, a turbiditic wacke unit about 850 m thick. The third major component of the structure is the collar of Archean and Proterozoic rocks that are intensely brecciated and shatter-coned in a zone some 10 to 15 km wide about the Complex.

The form of the Sudbury Igneous Complex has been postulated as a folded sill (Coleman 1905), a ring-dike complex (Knight 1923), or a funnel-shaped intrusion (Wilson 1956). As far as can be determined from surface and mine geology and exploration drilling, the

most likely shape is an asymmetric, funnel-shaped body with a northern limb dipping approximately 45° southward and a southern limb dipping at angles of 65°N to vertical.

Several major faults of the Murray System traverse the Sudbury Structure and there has probably been appreciable uplift of the southern half of the structure with respect to the northern half (Souch, Podolsky *et al.* 1969). The rocks of the southern part are weakly metamorphosed (subgreenschist, low greenschist facies). The Sudbury Igneous Complex and Onaping Formation of the northern part of the structure are unmetamorphosed.

The Footwall rocks south of the Sudbury Igneous Complex are mainly stratified Huronian metavolcanic and metasedimentary rocks and granitic rocks of the Creighton and Murray Plutons. The Huronian strata, which dip steeply and face southward, represent the northern limb of a major synclinalorium to the south.

The Footwall rocks on the northern side of the Sudbury Structure also, in a sense, "face" northward in that the oldest rocks, the Levack Gneiss Complex, occur next to the Sudbury Igneous Complex, and successively younger rock units, the Algoman "Granite" and Huronian metasedimentary rocks, occur increasingly farther north. A series of Huronian outliers forms a discontinuous ring north and west of Sudbury. These remnants appear to link the main Huronian Basin south and west of Sudbury with the Huronian of the Cobalt Embayment which lies north and east. The outliers may represent the outer rim of an impact crater some 100 km in diameter (Dence 1972), or the remnants of Huronian strata deposited in a paleovalley developed on the Archean surface. The fact that many of these remnants are synclinal rather than west-dipping monoclines would suggest that they represent paleovalley fill rather than the upturned collar of an impact crater.

ROCK DENSITIES

In order to interpret gravity models, information is required on the densities of the different rock types present in the study area. A large number of density measurements for rocks of the Sudbury region are available from 3 sources:

1. surface sample measurements collected by the Gravity Division, Earth Physics Branch (Popelar 1972)
2. surface sample measurements, immediately outside of the Sudbury area, collected by the Ontario Geological Survey (Gupta and Grant In Press)
3. measurements on surface and core samples from the Sudbury area specifically done for the present study

The density data are summarized in the frequency dia-

TABLE 18.2: DENSITIES USED IN COMPUTER MODELLING.

ROCK UNIT	AVERAGE MODEL DENSITY (g/cm ³)	
	MODEL A	MODEL B
Chelmsford and Onwatin Formations	2.73*	2.68
Sudbury Igneous Complex Upper Zone (Granophyre) and Onaping Formation	2.73*	2.71
Fairbank Granophyre	2.66	2.66
Sudbury Igneous Complex Lower Zone (Norite) and Sublayer	2.80	2.80
Levack Gneiss	2.77	2.77
Mafic Body in Onwatin Formation	2.85	2.85
Mafic Body under Elsie Mountain Formation	2.96	2.96
Hidden Body	—	3.02
Hidden Body (Southern)	3.08	—
Hidden Body (Northern)	3.02	—
Average Crust Background Density, Sudbury Region	2.73	2.73

* Model A requires zero density contrast for the Sudbury Basin rocks

grams shown in Figures 18.3 and 18.4, and densities used in gravity modelling are given in Table 18.2

Sudbury Igneous Complex, Lower Zone and Sublayer

Popelar's (1972) measurements of the densities of norite samples give a positively skewed distribution with a mean density of 2.85 g/cm³ and a modal density of 2.80 g/cm³. Recent core sample measurements show a slightly different distribution for norite, with a mean density of 2.81 g/cm³ and a modal density of 2.77 g/cm³ (Figure 18.3). Core samples from the Sublayer have a mean density of 2.86 g/cm³ and a modal density of 2.82 g/cm³.

Popelar's data on the Sudbury Igneous Complex rocks are not subdivided between Lower Zone (norite) and Sublayer (quartz gabbro) samples, and the frequency diagram shown in Figure 18.3a presumably contains both. The thickness of the Sublayer is roughly 1/3 that of the Lower Zone. If we were to combine the core sample measurements for the Lower Zone and Sublayer and weight them in proportion to the thicknesses of the 2 units, we would obtain a positively skewed distribution having a mean density of 2.82 g/cm³ and a modal density of 2.78 g/cm³. The "most probable" range (roughly the 80% confidence range) for the combined average density of the Lower Zone and the Sublayer is a density of about 2.76 to 2.84 g/cm³ with a bias toward the lower end. For modelling the residual gravity anomalies, a density of 2.80 g/cm³ has been assumed for the Lower Zone and the Sublayer.

Sudbury Igneous Complex, Middle Zone

Known also as the Transitional Zone (between norite

and granophyre), this unit (quartz gabbro) was not sampled by Popelar (1972). The core sample measurements have a mean value of 2.85 g/cm³ and a modal density of 2.82 g/cm³, with a wide distribution.

Sudbury Igneous Complex, Upper Zone

Popelar's (1972) density data for the Upper Zone (granophyre) have a positively skewed distribution with a mean density of 2.73 g/cm³ and a modal density of 2.68 g/cm³. The measurements by the Ontario Geological Survey show a slightly lower mean density of 2.71 g/cm³. The most probable range in density is about 2.66 to 2.73 g/cm³, with a bias toward the lower end. The density value that has been assumed for the Middle and Upper Zones of the Sudbury Igneous Complex is 2.69 g/cm³, and for the Fairbank Granophyre, 2.66 g/cm³.

Whitewater Group: Onaping Formation

Popelar's density data for the heterolithic breccias of the Onaping Formation have a symmetrical distribution with mean and modal values for the density of 2.73 and 2.71 g/cm³, respectively. Ontario Geological Survey data from surface and core samples show a somewhat negatively-skewed distribution for these rocks, with a mean value of 2.73 g/cm³ and a modal density of 2.77 g/cm³. The most probable range for the average density of the Onaping Formation is 2.69 to 2.78 g/cm³. An average density of 2.73 g/cm³ has been assumed. For modelling purposes, both the Sudbury Igneous Complex Upper Zone (granophyre) and the Onaping Formation have been combined into a single unit whose average density is estimated at 2.71 g/cm³.

Whitewater Group: Onwatin and Chelmsford Formations

Ontario Geological Survey density data on surface and core samples from the Onwatin and Chelmsford Formations have a complex, bimodal distribution with a mean value of 2.66 g/cm³ and modal values of 2.60 and 2.71 g/cm³. It is difficult to explain the sharp peak at 2.60 g/cm³. It is probably justifiable either to underweight or to exclude the densities of 2.60 g/cm³ and lower. This would result in a mean value of 2.68 g/cm³ and a modal value of 2.71 g/cm³ for the remainder of the samples, with a most probable range of 2.65 to 2.74 g/cm³. In modelling the Sudbury Basin, a combined average density of 2.68 g/cm³ has been assumed for the Onwatin and Chelmsford Formations.

Levack Gneiss Complex

The distribution of sample densities of the Levack Gneiss Complex is positively skewed, with a mean value of 2.77 g/cm³ and a modal value of 2.69 g/cm³.

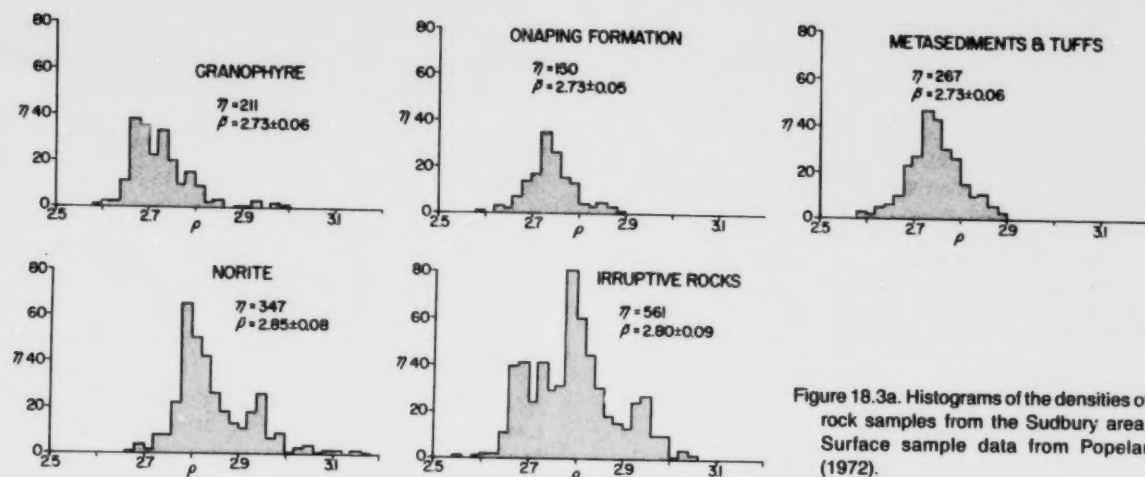


Figure 18.3a. Histograms of the densities of rock samples from the Sudbury area; Surface sample data from Popelar (1972).

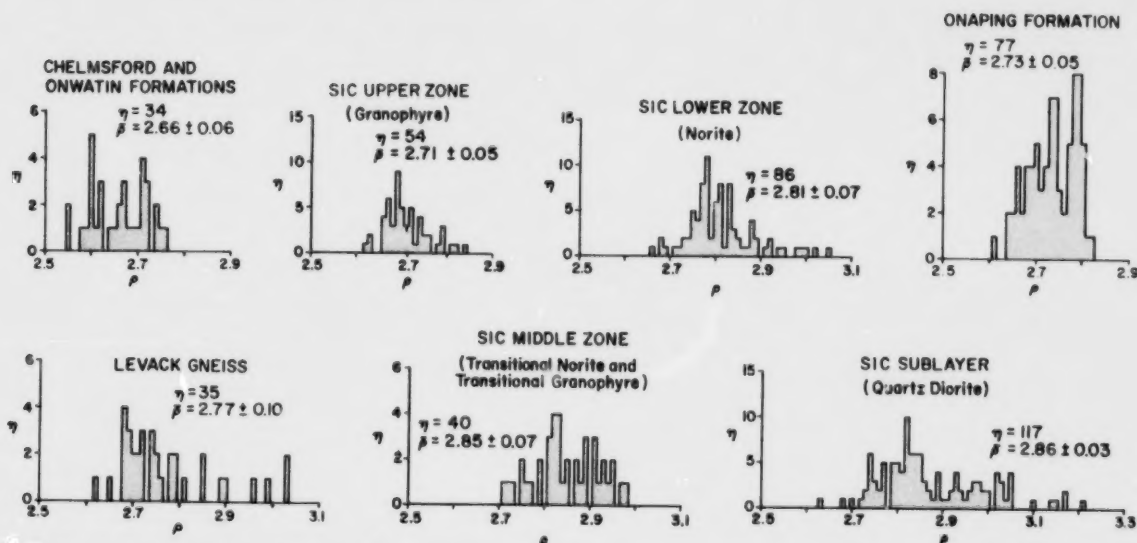


Figure 18.3b. Histograms of the densities of rock samples from the Sudbury area; Surface and core sample data acquired during the present study.

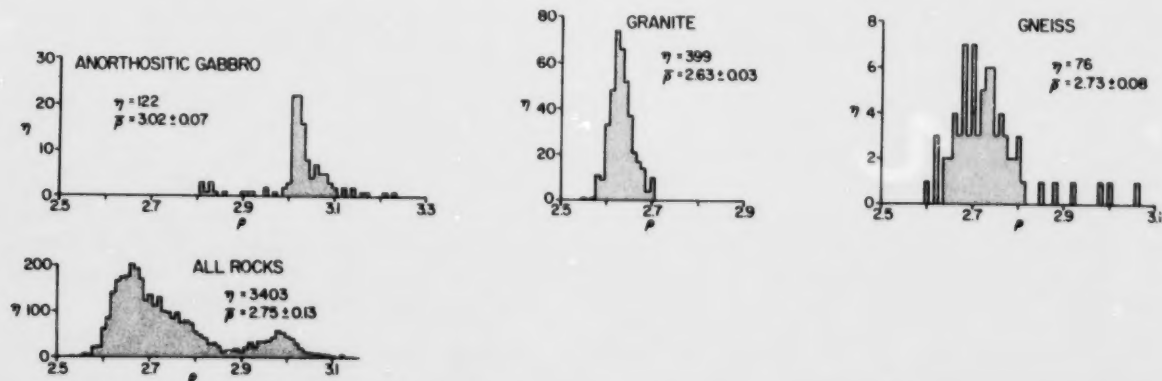


Figure 18.4. Density histograms of rock samples outside the Sudbury area from Gupta and Grant (In Press).

The 80% confidence range for the average density of Levack Gneiss Complex is approximately 2.69 to 2.80 g/cm³, indicating the extreme heterogeneity of these rocks. An average density of 2.77 g/cm³ has been assumed for modelling.

Anorthosite Gabbro

The data for anorthosite gabbros include both surface and core samples. The data have a symmetrical distribution with a mean and a modal density of 3.02 g/cm³, and a most probable range of 2.99 to 3.07 g/cm³ (Figure 18.4).

Granite

Samples of granites taken from a wide region surrounding the Sudbury area have a narrow, slightly positively-skewed distribution of sample densities with a mean density of 2.63 g/cm³ and a modal density of 2.62 g/cm³ (Gupta and Grant In Press). The most probable range is 2.60 to 2.66 g/cm³ (Figure 18.4).

Gneiss

Gneissic rocks collected from a large area north of Sudbury have a fairly symmetrical distribution of sample densities, with mean and modal values of 2.73 g/cm³ (Gupta and Grant In Press). The 80% confidence limits on the average density of these rocks are approximately 2.68 g/cm³ to 2.77 g/cm³.

Regional Background Density Value

The density differences that are used in fitting the gravity anomalies by computer, or that are calculated during the anomaly inversion process, are given in relation to the background density for the region. The background density is the average density of the "country rock", meaning a typical crustal section containing the most common rock types which surround and underlie the Sudbury Structure. In order to determine the densities of individual rock units, hence their mineralogies, a value for background density must be assumed.

It is an easy matter to establish upper and lower bounds for the density of the country rock within the study region. Granites (average density = 2.63 g/cm³) invariably produce gravity lows, therefore, the background density must be greater than that of granites. Mafic metavolcanic rocks of the Benny Greenstone Belt (average density = 2.83 g/cm³) produce gravity highs, so that the background density must be less than that of mafic metavolcanic rocks. The most common rock type in the gravitationally flat region that lies to the north and west of Sudbury is gneiss, whose average density is about 2.73 ± 0.08 g/cm³. The rocks which make up the terrain surrounding the Sudbury Structure over a distance of many 10s of km consist of gneiss

(average density = 2.73 g/cm³), granites (average density = 2.63 g/cm³), metasedimentary rocks including paragneiss (average density = 2.73 g/cm³), diabase/gabbro (average density = 2.95 g/cm³), and "greenstones" (average density = 2.83 g/cm³). From 3403 rock density measurements carried out in the vicinity of the Sudbury area, an average density for these different rock types, weighted according to their relative areas of mapped surface exposure using the geological compilation work of Card and Lumbers (1975), and excluding the Sudbury Structure itself, is 2.73 g/cm³ (see Table 18.1).

The most rational choice for a background density, therefore, would seem to be about 2.73 g/cm³. This value is not rigidly fixed, of course, and can probably be revised upward or downward by as much as 0.02 g/cm³. This density probably cannot be changed by much more than this, since the norites within the Lower Zone of the Sudbury Igneous Complex, whose measured average density is about 2.81 ± 0.07 g/cm³, produce weak positive anomalies, while the Onwatin and Chelmsford Formations, whose measured average density is about 2.66 ± 0.06 g/cm³, produce weak negative effects. For the purpose of geological interpretation, 2.73 g/cm³ would thus appear to be a reasonable choice for the background density value.

THE SUDBURY GRAVITY ANOMALY

Choosing a Base Level for the Local Gravity Field

The first step in analyzing the Sudbury gravity anomaly is to determine its amplitude, which means establishing a background value for Bouguer gravity within the Sudbury region. Since there is not sufficient prior knowledge of the thickness and composition of the earth's crust in the Sudbury region to calculate the normal Bouguer gravity field theoretically, it must be determined empirically. To do this, Bouguer gravity data must be examined over a broader region than the area surrounding Sudbury. The area chosen extends from Latitudes 46°N to 48°N and from Longitudes 80°W to 82°W. The Sudbury Structure lies almost in the centre of this broad region (see Bouguer gravity maps, Charts A and C, back pocket).

The method used for determining normal Bouguer gravity is the conventional one of baselevelling anomalies along profiles arranged on a regular grid, using regional geological mapping and measured densities as a guide, and joining the local baselevels by smooth, intersecting curves. The profiles were chosen to be north-south and east-west, and were taken at 9 km intervals throughout the 2° by 2° region. The Sudbury part of the regional Bouguer gravity field that is gen-

erated by this process is shown in Figure 18.5. As the contours indicate, the regional field is extremely smooth, reflecting density changes occurring within the upper mantle or lower part of the crust. Although the method that was used in constructing this field is subjective, in the sense that the work is performed graphically and involves personal judgment, the geological mapping and the need to maintain very smooth gradients provides fairly tight controls over the positioning of the local base levels. The authors estimate that the regional gravity values indicated in Figure 18.5 could be revised upward or downward at any point by not more than 2 mgal, except possibly near the southeastern corner of the area (for example, south of the Grenville Front) where changes as large as 4 mgal might be accommodated. This would have to be done in such a manner that the regional contours remain smooth.

Figure 18.5 is a contour map of the normal Bou-

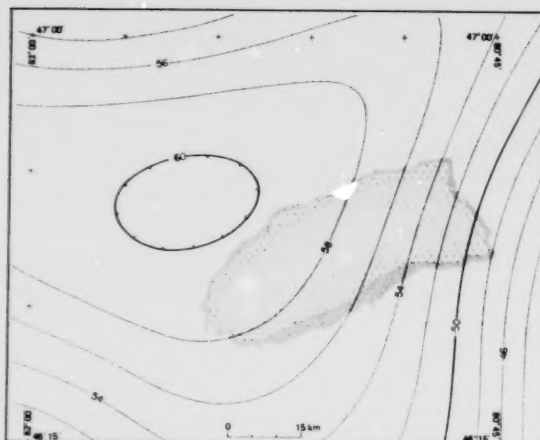


Figure 18.5. Regional or normal Bouguer gravity field. Contour interval is 2 mgal.

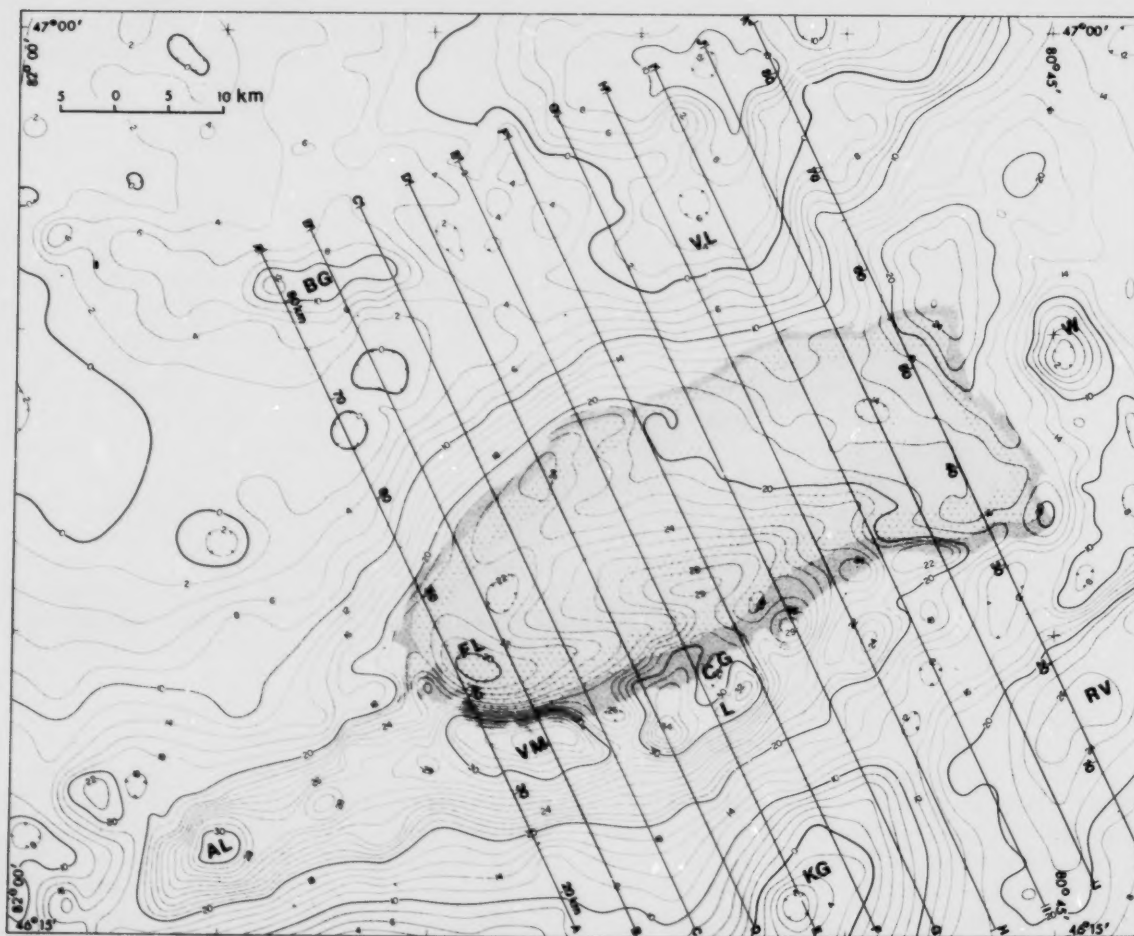


Figure 18.6. Anomalous Bouguer gravity field. Location of profiles is also shown. BG = Benny Greenstone Belt; AL = Agnew Lake Anorthosite Gabbro; VM = Victoria Mine gravity high; L = Lively gravity high; RV = River Valley anorthosite complex; KG = Killarney Granite Pluton; CG = Creighton Granite; VL = Venetian Lake Granite Pluton; W = Lake Wanapitei; FL = Fairbank Lake Granophyre.

guer gravity field within the study area, which excludes effects due to density variations occurring within the upper levels, roughly speaking, within about the top 10 to 15 km of the earth's crust. By subtracting this field from the observed Bouguer gravity (Figure 18.1), the anomalous Bouguer gravity component shown in Figure 18.6 is obtained. Figure 18.6 is a contour map of the gravity effects that are caused by density variations occurring within the upper part of the earth's crust. It is the "geological" component of the Bouguer gravity field shown in Figure 18.1. The most prominent features of Figure 18.6 are:

1. the Sudbury positive gravity anomaly
2. negative gravity anomalies over the Killarney Granite Pluton (KG), the Venetian Lake Granite Pluton (VL), and also over Lake Wanapitei (W) which has been interpreted as a possible meteorite impact crater (Dence and Popelar 1972)
3. positive anomalies over the Benny Greenstone Belt (BG), the Agnew Lake Anorthosite Gabbro (AL), the Victoria Mine (VM) and Lively (L) gravity highs under the Elsie Mountain and Stobie Formations, and over the River Valley Anorthosite Complex (RV).

The strong, clearly defined negative anomalies over the granites show that their density (2.62 to 2.65 g/cm^3) is below that of the average crustal rocks within this region. The positive anomalies over the Benny "Greenstones" (density 2.83 g/cm^3), the Agnew Lake

Gabbro-Anorthosite (density 3.0 g/cm^3), and the River Valley Anorthosite (density 2.9 to 3.1 g/cm^3) indicate that the densities of these rocks are above the crustal average.

The rest of the area to the north and west of the Sudbury Structure is flat gravitationally, indicating a region of fairly uniform density. Except for the Benny Greenstone Belt and the Venetian Lake Granite Pluton, this region is mapped as gneiss with a few minor enclaves of granite. Between the Sudbury Structure and the Grenville Front, the rocks are mapped as metasedimentary rocks mixed with minor metavolcanic rocks. It is difficult to ascertain from Figure 18.6 whether these supracrustal rocks have a density that is significantly different from that of the gneiss.

Analyzing the Sudbury Gravity Anomaly

Separation of the anomalous Bouguer gravity (Figure 18.6) into "major" and "minor" ("regional" and "residual") components is illustrated by the 9 north-northwest-trending profiles shown in Figure 18.7, whose locations are given in Figure 18.6. The basis for drawing these curves is similar to that which was used in preparing the map of "normal" Bouguer gravity shown in Figure 18.5, for example, local anomalies associated with known geological features such as the Killarney Pluton, the Venetian Lake Granite Pluton,

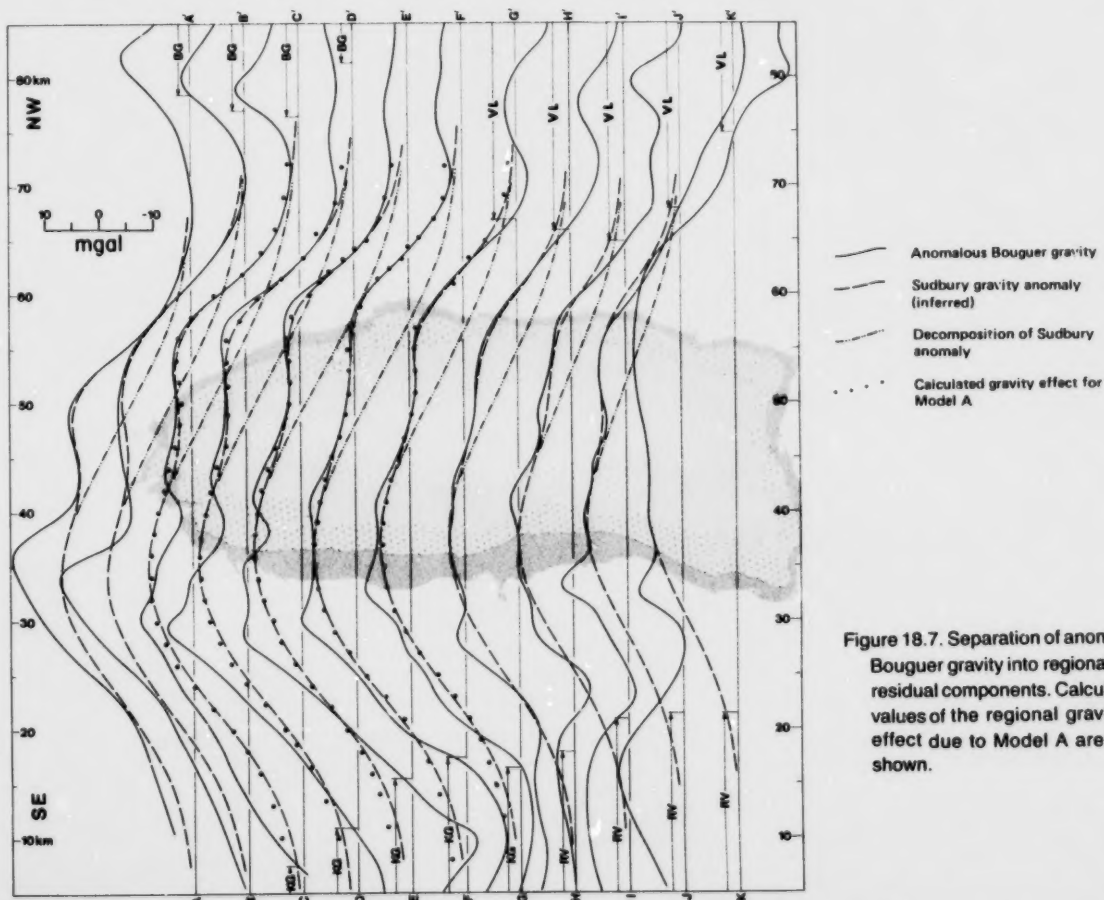


Figure 18.7. Separation of anomalous Bouguer gravity into regional and residual components. Calculated values of the regional gravity effect due to Model A are also shown.

and the Benny Greenstone Belt are baselevelled, and smooth curves are fitted to the remaining parts of the profiles. The fitting is constrained by the necessity of maintaining equal smoothness in the baselevels both transverse to the profiles and along them, and by the use of a bias which favours positive residual anomalies over the more mafic rocks that lie immediately to the south of the Sudbury Igneous Complex. It would be difficult to alter the regional component at any point by much more than 1 mgal. From the smoothed profiles, the gravity contours shown in Figure 18.8 are obtained. These contours represent the form that the Sudbury gravity anomaly would presumably take if all local, near-surface gravity effects were removed. This gravity feature is obviously caused by rocks which lie at some significant depth below the ground surface.

The residual gravity component that remains when the main Sudbury anomaly (Figure 18.8) is subtracted from the anomalous Bouguer gravity field (Figure 18.6), is shown in Figure 18.9. (Figure 18.9 does not include the whole of the study area, but only that part containing the main part of the Sudbury anomaly). These residual anomalies represent the gravity effects of rocks which are at or very close to the

ground surface. The most prominent features of this map are the strong positive anomalies that correlate with the basaltic volcanic rocks of the Elsie Mountain Formation situated near the southern margin of the Sudbury Structure, and the negative anomaly that is centred on the granophyre at Fairbank Lake near the southwestern corner of the Sudbury Igneous Complex. There is a weak residual gravity low over the Sudbury Basin, and some very minor highs (generally < 2 mgal) over the Lower Zone of the Sudbury Igneous Complex at several locations. A distinct, linear residual gravity high of approximately 2 mgal exists within the Onaping Formation on the southern side of the Sudbury Basin.

Gravity Anomaly Interpretation

The Sudbury gravity anomaly shown in Figure 18.8 is a complex, double-peaked feature, as is evident from the gravity profiles shown in Figure 18.7. It has a northern and a southern "ridge", the latter being the larger of the two. There are 2 alternative ways of viewing this anomaly, leading to 2 different interpretations of its origin: (a) it consists of 2 single-peaked, positive

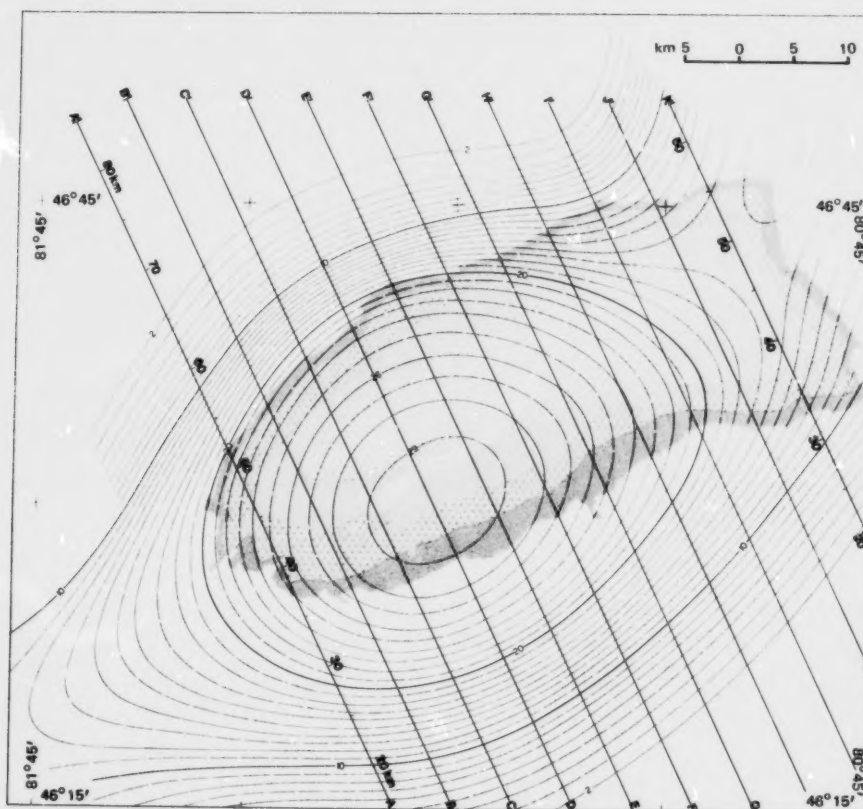


Figure 18.8. Sudbury gravity anomaly ("regional" component of anomalous Bouguer gravity). Contour interval is 1 mgal. Locations of profiles are also shown.

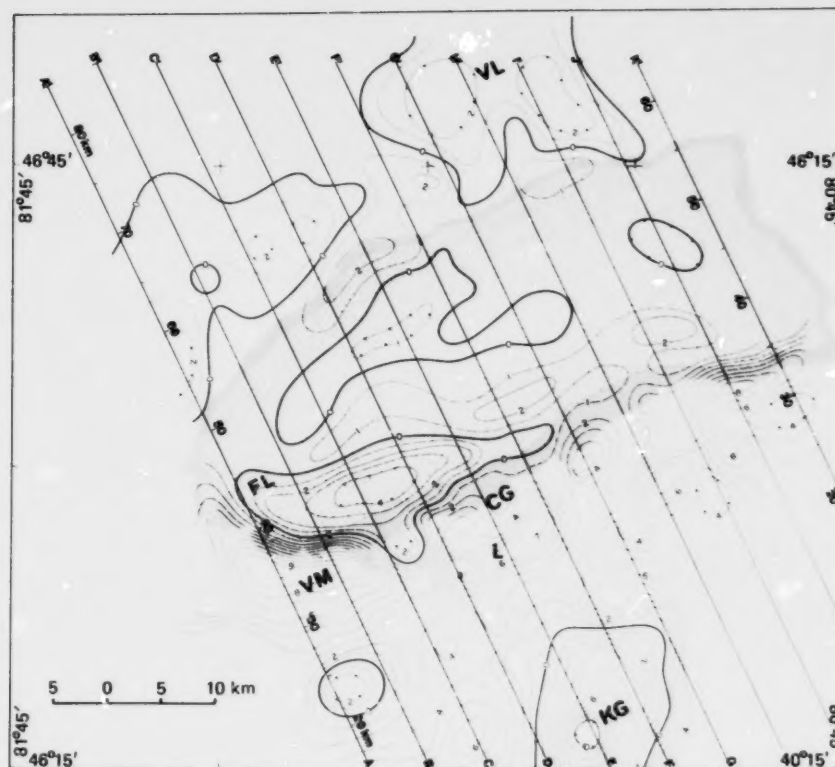


Figure 18.9. Residual Bouguer gravity. Contour interval is 1 mgal. Locations of profiles are also shown.

anomalies which are overlapping (Model A); or (b) it consists of a single positive anomaly with a smaller negative anomaly superimposed upon it (Model B). The only other possibility is that the anomaly is due to a single, positive mass of complex shape. This is just a special case of Model A which attributes the anomaly to 2 positive bodies, except that in this case the 2 densities are assumed to be the same.

Model B is illustrated in Figure 18.10, which shows the decomposition of the main anomaly into positive and negative components. The separation is necessarily subjective, but it would be difficult to vary either component by as much as 2 mgal anywhere. The positive anomaly is shown in Figure 18.11, and the negative anomaly in Figure 18.12.

Support for Model A comes mainly from the aeromagnetic contour map, which reveals a magnetic anomaly coinciding closely with the northernmost of the 2 positive gravity components. For Model B, supporting evidence lies mainly in the coincidence of the negative gravity component with the Sudbury Basin and granophyre rocks. This suggests that the White-water Group rocks, together with the granophyre, may be slightly less dense than the surrounding gneissic rocks.

Interpretation Methods

The geophysical interpretation of the gravity anomalies has been performed by mathematical inversion or computer modelling, using the method of least squares (see Enmark 1981). The models, referred to as 2½-D models, are polygonal in cross-section, of uniform density contrast with the surrounding rocks, and are of finite strike length (after Cady 1980). The models do not plunge along their strike. The interpretations are carried out upon one gravity profile at a time, using interactive programming which allows for the progressive shifting of the centres of the bodies relative to the profile positions. Two or more bodies can be fitted simultaneously, with constraints being applied to prevent intersections from occurring.

One of the more powerful features of inverse methods is that they do not require any prior assumptions to be made concerning the densities of the models, other than the specification of upper and lower limits. This gives them a significant advantage over the older "forward" methods, which depended very critically upon the prior assumption of density values. Computer modelling will yield "best" values for the density contrasts of the various bodies relative to the background density, in the sense that these values pro-

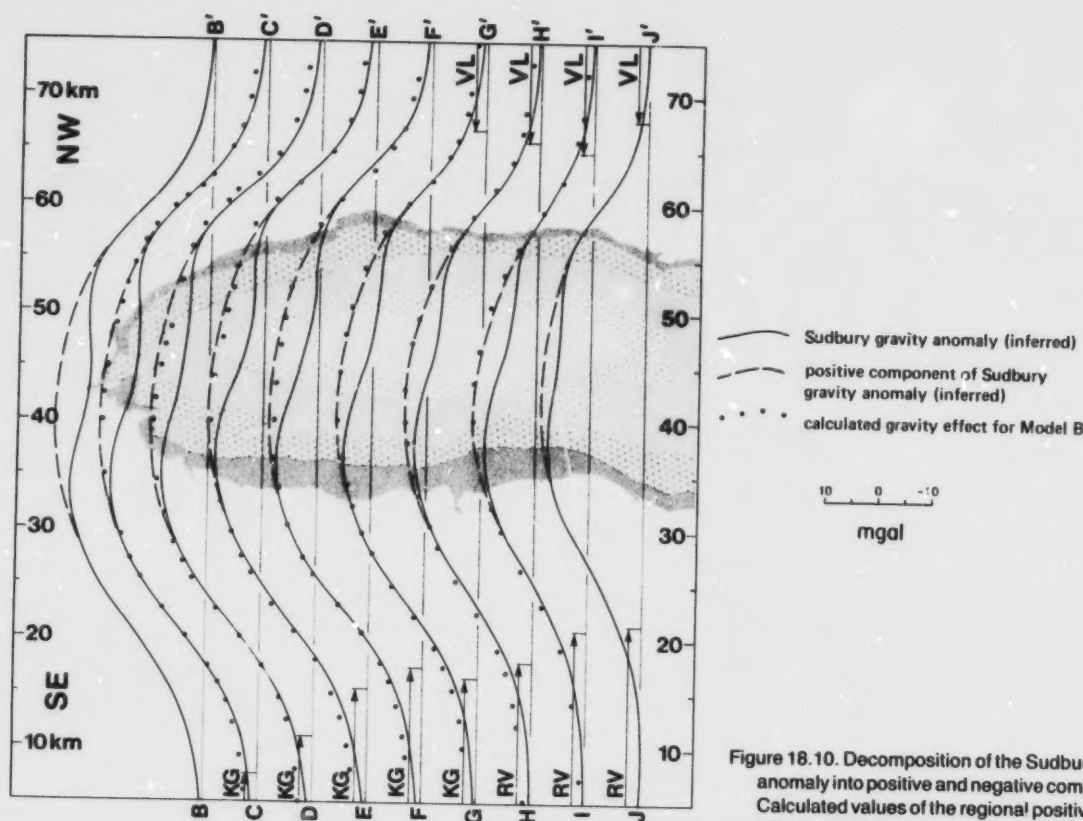


Figure 18.10. Decomposition of the Sudbury gravity anomaly into positive and negative components. Calculated values of the regional positive gravity effect due to Model B are also shown.

duce a global minimum in the sum of squares of the deviations between the observed gravity anomaly and the calculated gravity effects of the models at the points chosen for fitting. The "best" density values, together with their respective confidence ranges, can be referred to a table of densities of the rocks within the study region in order to arrive at a geological interpretation. This approach to finding a "best" density directly from the gravity observations differs somewhat from Parker's (1974) "ideal body" algorithm, but it is less costly to use when a large number of data are involved.

By varying the starting values of the parameters which define the interpretational models, a set of mass configurations can be found which are defined by upper and lower bounds on the defining parameters, and which will minimize the sum of squares of the deviations between the observed and calculated gravity fields at a given set of points. These configurations are never unique, since a different choice of model will inevitably lead to a different interpretational result, but they effectively establish limits on the solution which, in practical terms, are probably more useful than an answer that is stated precisely, but which has a high degree of mathematical uncertainty. The computer modelling results, which are mathematical generalizations of the actual geological situation, are used as a

basis for geological interpretation, in which all available surface and subsurface controls are also used.

Sudbury Gravity Modelling

The 2 geophysical interpretations of the Sudbury gravity anomaly are referred to as Model A, which assumes 2 overlapping positive, single-peaked anomalies and Model B, which assumes a single positive and a single negative anomaly which are superimposed.

MODEL A

Model A is determined by first separating the Sudbury gravity anomaly into 2 positive components, and then by calculating mass configurations which will reproduce the 2 positive anomalies separately and together. The manner in which the anomaly is separated has a critical impact upon the results, and this first step is, therefore, crucial.

In Figures 18.7 and 18.8, the 2 components of the Sudbury gravity anomaly are not sufficiently resolved to permit them to be easily separated. However, the resolution can be improved by continuing the gravity field downward toward its source as illustrated in Figure 18.13, which shows profiles of the Sudbury anomaly.

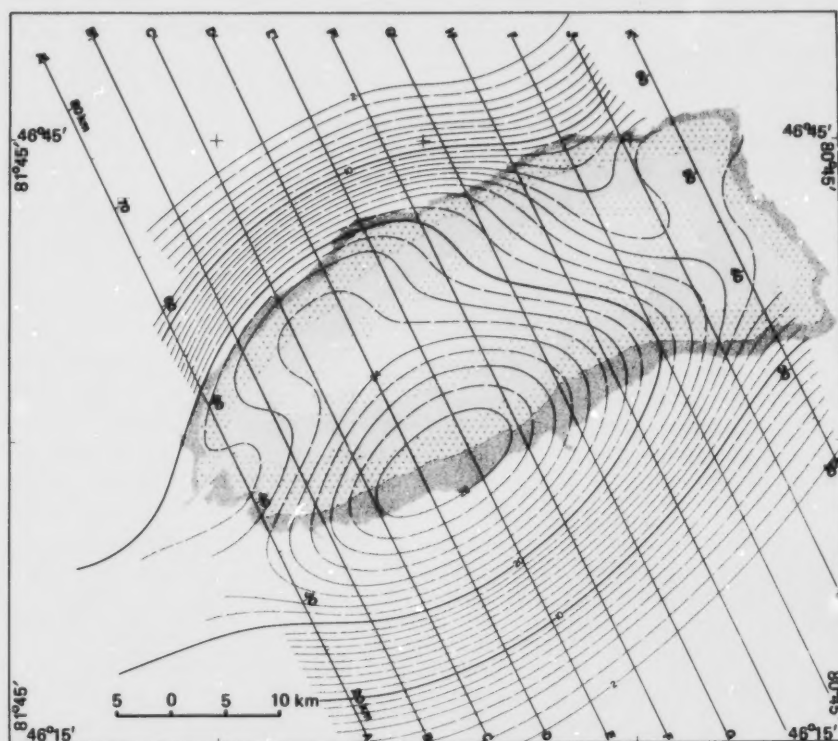


Figure 18.11. Positive component of the Sudbury gravity anomaly, according to decomposition shown in Figure 18.10. Contour interval is 1 mgal. Locations of profiles are also shown.

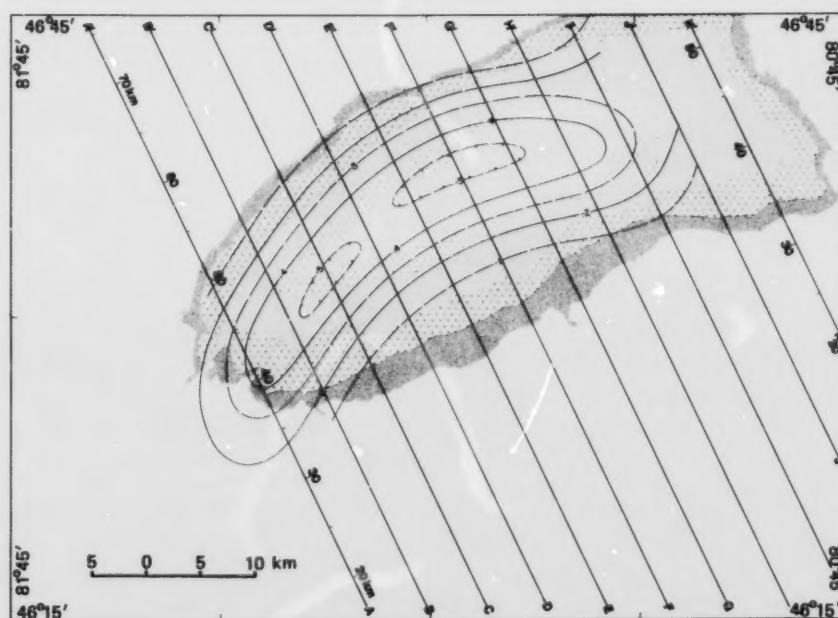


Figure 18.12. Negative component of the Sudbury gravity anomaly, according to decomposition shown in Figure 18.10. Contour interval is 1 mgal. Profile locations are also shown.

ally continued downward to a depth of 3 km. These profiles clearly demonstrate that downward continuation amplifies the northern part of the anomaly much more than the southern part, indicating that this part of the anomaly probably originates from a shallower source than the remaining part. The separation of the 2 anomalies was performed at ground level, using graphical methods. It is a subjective procedure, and many solutions are possible. We have chosen the one that gives the smoothest shapes for the 2 anomalies. "Smoothest shapes" can be defined by various mathematical criteria. In this study, maximum smoothness has been equated with minimum horizontal gradients. The 2 anomalies were inverted separately, and a final fit to the composite gravity anomaly has been made by adjusting the 2 solutions simultaneously. The intermediate steps are somewhat mechanical. The final results appear in Figure 18.14 on 5 profiles (CC' to GG') spaced 5 km apart along the length of the Sudbury Structure, together with the results of modelling work that was carried out on the residual anomalies (shown in Figure 18.9), which will be discussed below.

Southern Anomaly

Using a strike-limited, dipping prism as a starting interpretational model, the southern component of the Sudbury gravity anomaly is indicated to be due to a large, subhorizontal, sill-like mass. The depth to its top appears to be > 6 km and < 9 km, with a density contrast of more than $+0.3$ g/cm³ and an average thickness of about 3 km. Thickness will change with density

contrast in roughly an inversely proportional manner so that the product of density contrast and thickness remains approximately constant.

Northern Anomaly

The northern component of the Sudbury anomaly is indicated to be due to a dike-like body with a southward dip of about 30° to 40° and a density contrast of $+0.25$ g/cm³ or greater. It has a horizontal thickness of approximately 4 km, and it appears to be buried at a depth of between 2 and 5 km.

These initial, very simple cross-sectional forms were later generalized by making them into polygons of 6 and 4 sides for the southern and northern bodies, respectively, and determining optimum co-ordinates for the 10 vertices by $2\frac{1}{2}$ -D interactive least squares inversion. This procedure resulted in the forms shown in Figure 18.14. As Figure 18.7 indicates, their combined calculated gravity effect matches the Sudbury anomaly profiles quite accurately.

Density and Depth Matrix Search: Model A

The inversion procedure is fairly unambiguous concerning the general forms that the 2 bodies must take (sill-like for the larger body to the south and dike-like for the smaller body to the north), but it is able to specify density contrasts, depths, and volumes only within broad confidence limits. The general shapes of the 2 bodies were kept more or less invariant. The optimization procedure was carried out on both bodies using

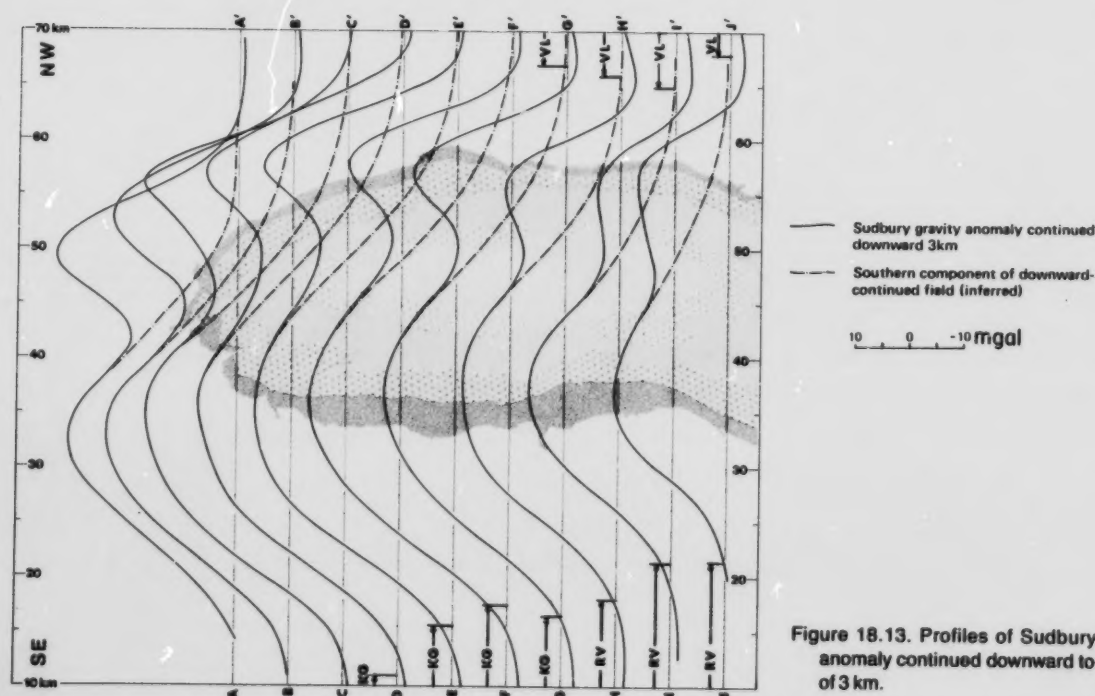


Figure 18.13. Profiles of Sudbury gravity anomaly continued downward to a depth of 3 km.

a number of different density contrasts and placing the bodies initially at several different starting depths. For each combination of density contrast and trial depth, the bodies were "optimized" so that their gravity effects provided a best least-squares fit to the Sudbury gravity anomaly. The results of this matrix search for "best" values of density contrast and depth of burial are shown in Figure 18.15.

SOUTHERN BODY

Figure 18.15a shows contours of the minimized standard deviation (in mgal) between the calculated and ob-

served Bouguer gravity values for the "sill" model of the southern body on a plot of final (optimized) depth of burial versus assumed density contrast. The contours indicate that for a body having a slab-like, sub-horizontal shape, the standard deviation is at or very near a global minimum when the depth of burial is between 6 and 9 km, and the density contrast is between 0.30 and 0.55 g/cm³ (Figure 18.15a). These ranges constitute the best estimates of density contrast and depth that can be made from gravity observations. The thickness estimate is given approximately by $1.2/\Delta\rho$ km, where the density contrast $\Delta\rho$ is in g/cm³.

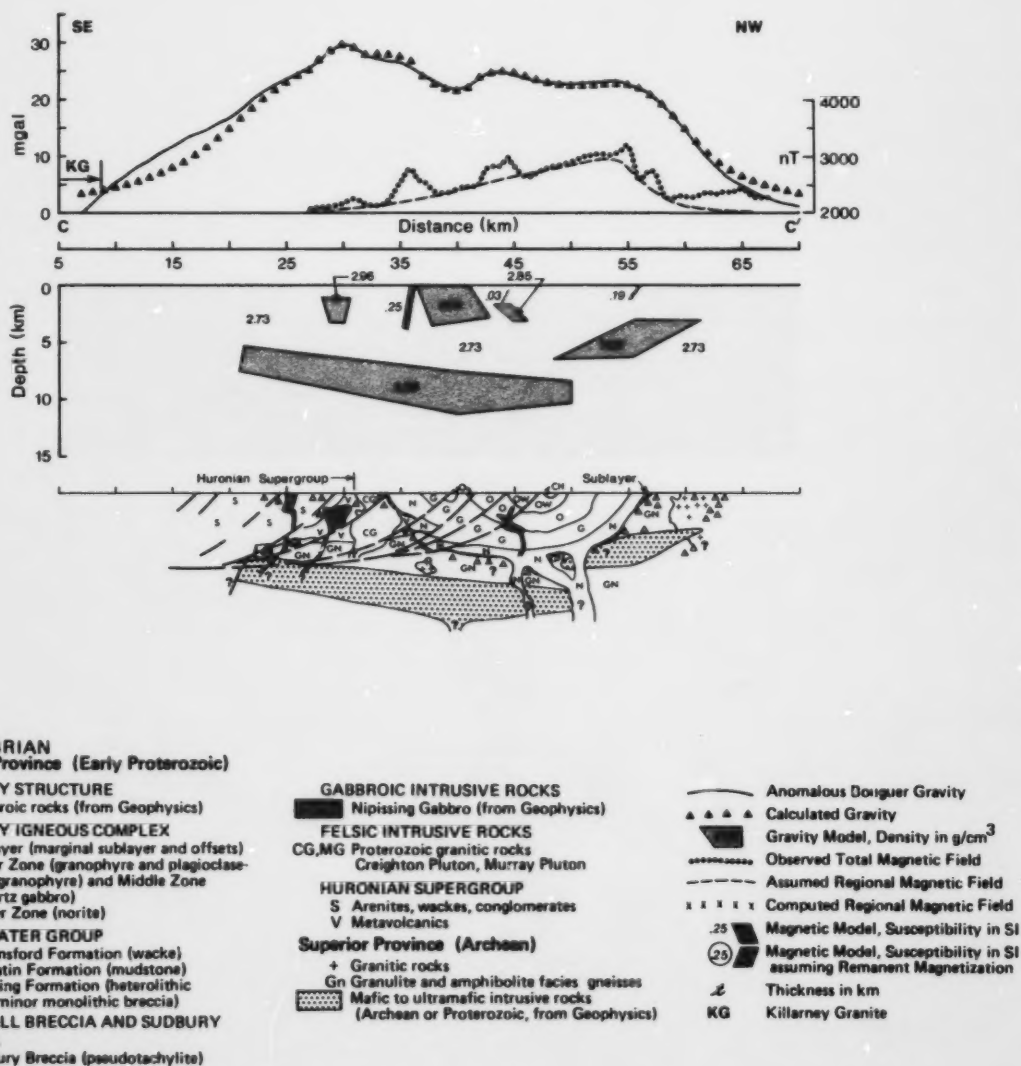


Figure 18.14. Profiles CC' to GG' showing the composite gravity interpretation consisting of Sudbury gravity anomaly Model A and residual anomalies. Computed near surface magnetic models for profiles CC' to GG' and regional magnetic model for profile EE' are also shown. Legend for the generalized geological cross-sections (supplied by Burkhard O. Dressler, Geologist, Ontario Geological Survey) based on gravity and magnetic models, is shown on the figure.

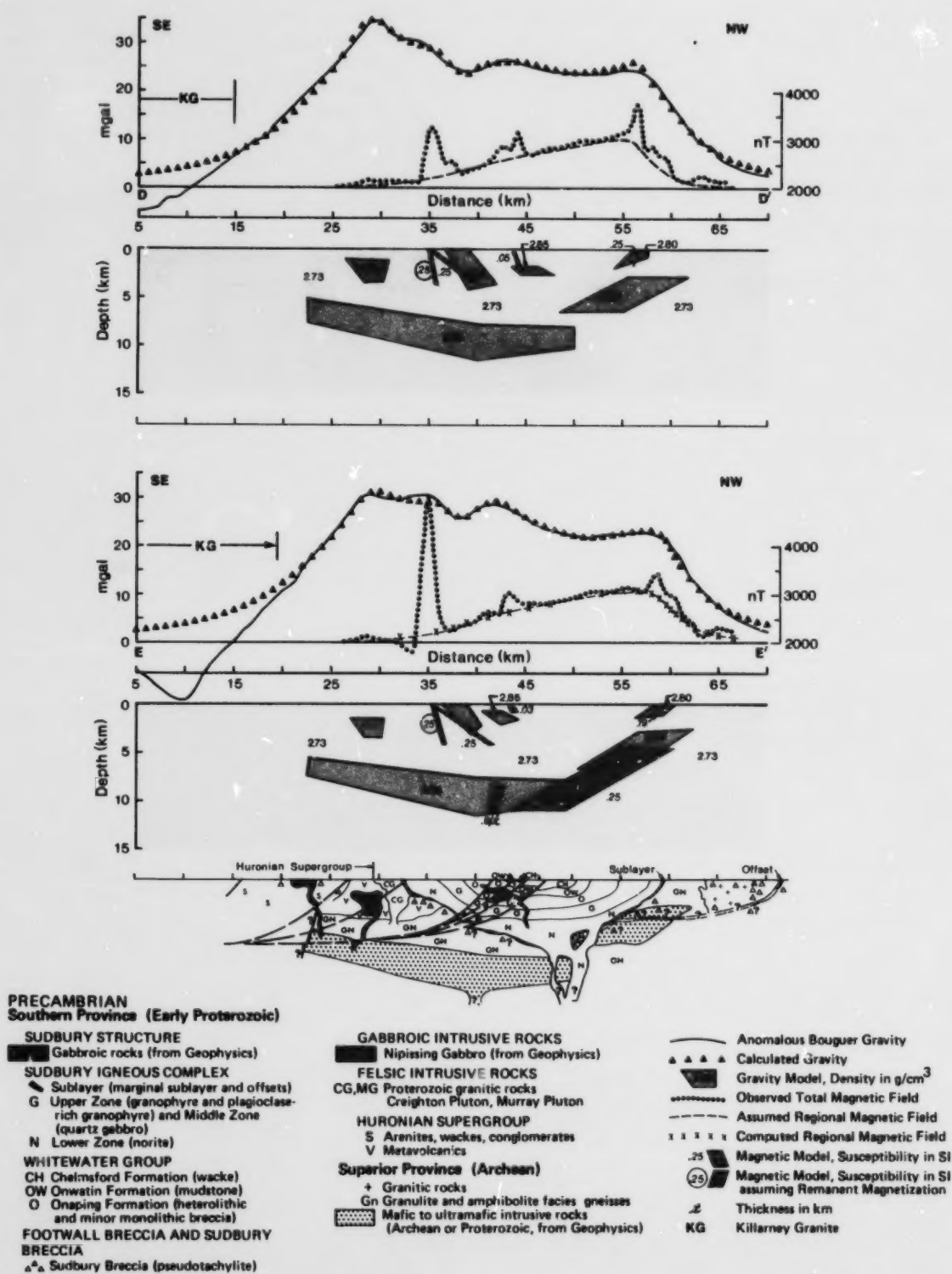


Figure 18.14. Profiles CC' to GG' showing the composite gravity interpretation consisting of Sudbury gravity anomaly Model A and residual anomalies. Computed near surface magnetic models for profiles CC' to GG' and regional magnetic model for profile EE' are also shown. Legend for the generalized geological cross-sections (supplied by Burkhard O. Dressler, Geologist, Ontario Geological Survey) based on gravity and magnetic models, is shown on the figure.

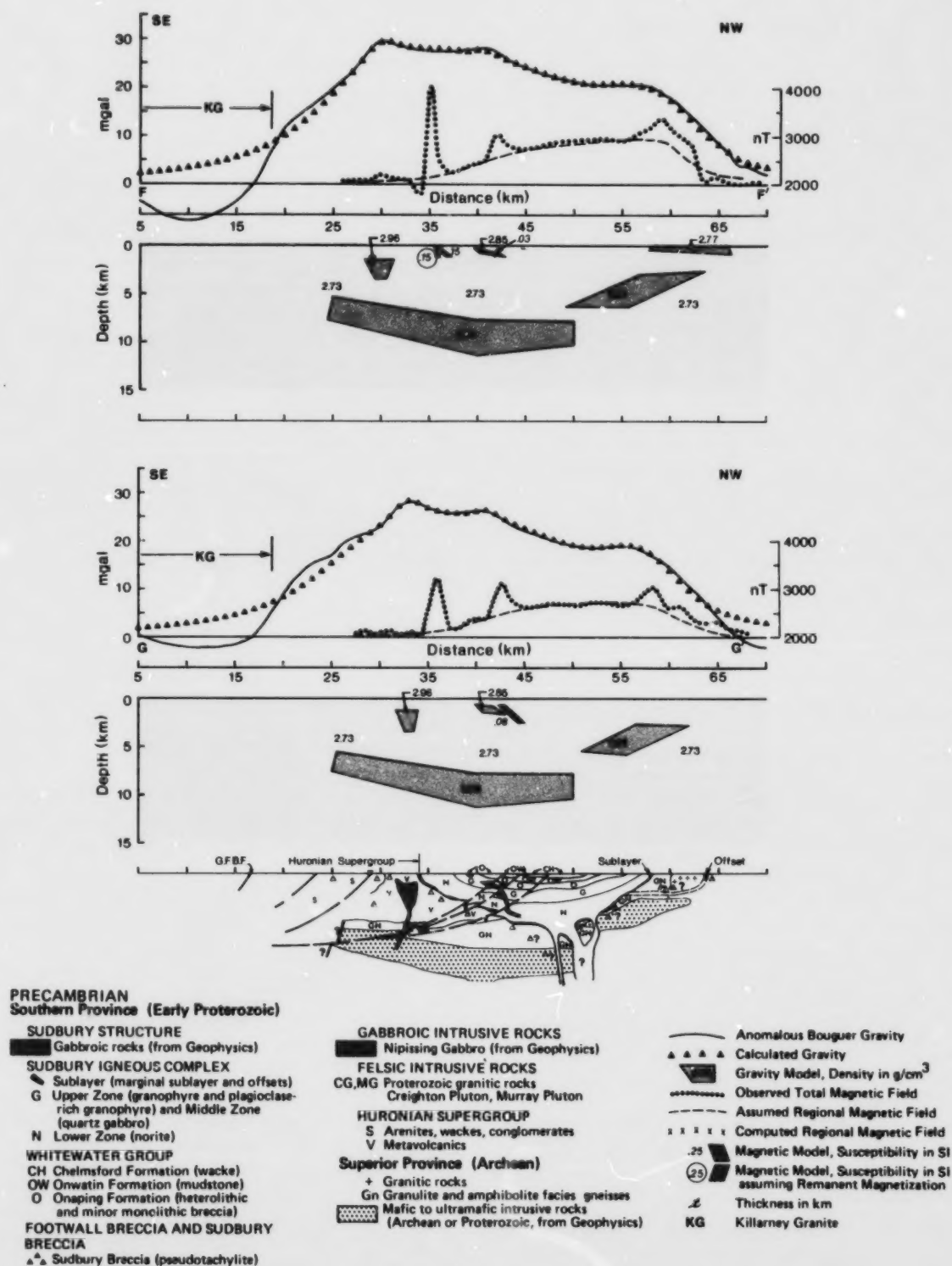


Figure 18.14. Profiles CC' to GG' showing the composite gravity interpretation consisting of Sudbury gravity anomaly Model A and residual anomalies. Computed near surface magnetic models for profiles CC' to GG' and regional magnetic model for profile EE' are also shown. Legend for the generalized geological cross-sections (supplied by Burkhard O. Dressler, Geologist, Ontario Geological Survey) based on gravity and magnetic models, is shown on the figure.

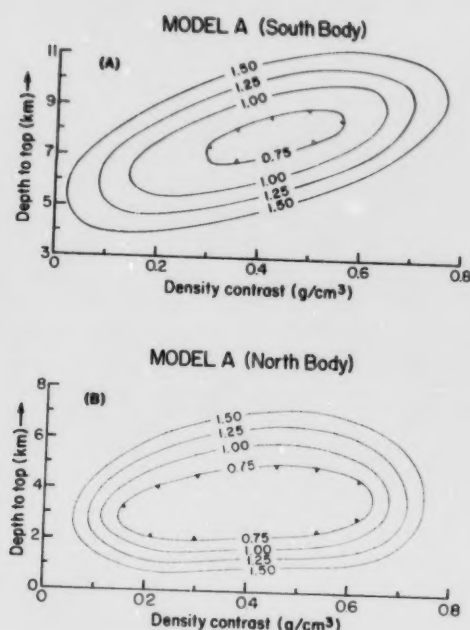


Figure 18.15. Minimized standard deviation (in mgal) between calculated gravity effect (Model A) and graphically separated Bouguer anomaly values; (a) for southern body, (b) for northern body.

NORTHERN BODY

Figure 18.15b is based upon a 2½-D dike-like model for the northern body. The best estimate that can be made from gravity for the depth of burial of this mass is between 2 and 5 km, and for its density contrast, a value between about 0.25 and 0.50 g/cm³ (Figure 18.15b). Again, the thickness of the body varies inversely with the density contrast, but not in a proportional manner.

The limits on the density contrast for the shallow northern body are slightly lower than those determined for the deeper southern body. However, the overlap is such that one cannot assert that the 2 bodies have different average densities. However, there is one respect at least in which the mineralogies of the 2 bodies must be different, since the shallow northern body is strongly magnetic, whereas the deeper southern body is non-magnetic or only weakly magnetic.

MODEL B

Model B is the result of performing inversions of the positive and negative anomalies (shown in Figures 18.11 and 18.12), along the 6 gravity profiles CC' to HH', inclusive. There was one important difference in the manner in which these and the previous inversions were carried out. The positive mass, which is totally hidden, is assumed to have a constant density, but otherwise it was left completely unconstrained. The neg-

ative mass, on the other hand, is assumed to have a layered structure representing the Sudbury Basin rocks and the granophyre, and the contact locations of these units at the ground surface are constrained by geological mapping.

Negative Anomaly

The outer layer of the negative mass represents the granophyre and the Onaping Formation. It was assigned a density contrast of -0.02 g/cm³ relative to the background density value. The inner layer represents the Onwatin and Chelmsford Formations. It was assigned a density contrast of -0.05 g/cm³ relative to the background value (for the derivation of these values see section on Rock Densities). These density contrasts were not allowed to vary, and neither were the surface limits of the 2 layers, which were fixed at their geologically mapped positions. The inversion of the negative anomaly consisted in determining cross-sectional forms for the layered structure which produced best fits to the gravity profiles, subject to the imposed constraints upon density contrasts and surface positions. The negative mass is basin-like in form, with a maximum depth extent of about 4.5 ± 0.5 km (Figure 18.16). On some of the profiles the dips of the layers appear to be steeper along the northern side than along the southern, which is opposite to what is indicated by surface and mine geology. However, there are several ways in which this apparent contradiction could be accounted for, including a relative thickening of lighter material on the northern side of the basin or a northward thrusting along the southern wall below the surface. With appropriate thickening or thinning of the different units which make up the model layers, it is not essential that the structural axis and the gravity axis should coincide.

The model that was used for fitting the negative gravity anomaly contains 10 degrees of freedom, corresponding to the x, z coordinates of the 5 unconstrained polygonal vertices. The shape of the negative anomaly, however, is not known with nearly the precision or control that is needed in order to solve uniquely for so many parameters. A total of 3 or possibly 4 parameters is probably all that could be determined from this anomaly with confidence. Accordingly, it cannot be said that the basin structure shown in Figure 18.16 has been determined from the gravity inversion process in any unique sense. All that can be said is that these forms are consistent with the shape of the negative anomaly and with the surface geology. To the extent that the model is correct, therefore, they represent plausible solutions.

Positive Anomaly

Using the prism model, a reasonably good overall fit to the positive anomaly (Figure 18.11) can be obtained with a horizontal slab at a depth of about 5 km, having

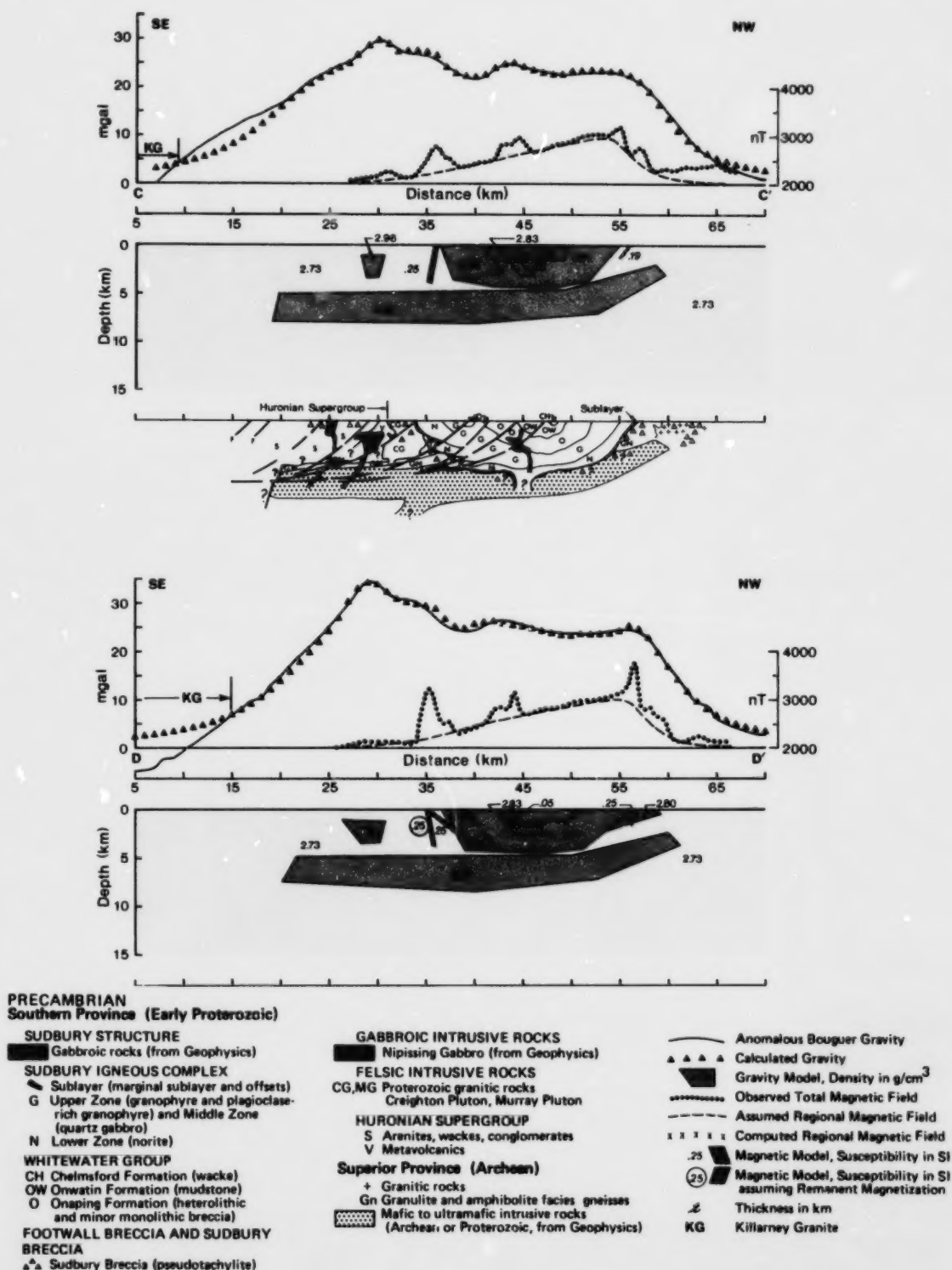
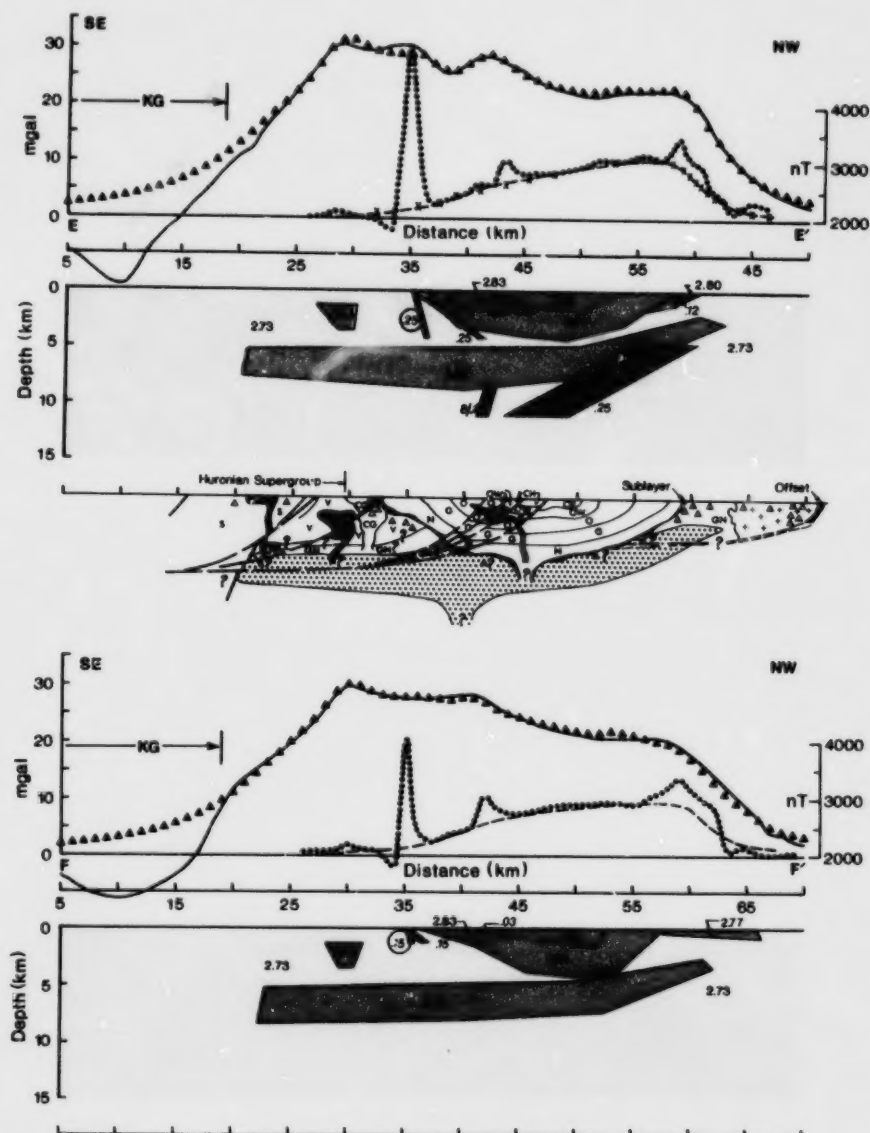


Figure 18.16. Profiles CC' to HH' showing the gravity interpretation consisting of Sudbury gravity anomaly Model B and residual anomalies. Near surface models computed from residual magnetic anomalies on profiles CC' to HH' and regional magnetic model for profile EE' are also shown.



PRECAMBRIAN Southern Province (Early Proterozoic)

SUDBURY STRUCTURE

Gabbroic rocks (from Geophysics)

SUDBURY IGNEOUS COMPLEX

Sublayer (marginal sublayer and offsets)

G Upper Zone (granophyre and plagioclase-rich granophyre) and Middle Zone (quartz gabbro)

N Lower Zone (norite)

WHITWATER GROUP

CH Chelmsford Formation (wacke)

OW Onwatin Formation (mudstone)

O Onaping Formation (heterolithic and minor monolithic breccia)

FOOTWALL BRECCIA AND SUDBURY BRECCIA

▲▲ Sudbury Breccia (pseudotachylite)

GABBROIC INTRUSIVE ROCKS

Nipissing Gabbro (from Geophysics)

FELSIC INTRUSIVE ROCKS

CG, MG Proterozoic granitic rocks

Creighton Pluton, Murray Pluton

HURONIAN SUPERGROUP

S Arenites, wackes, conglomerates

V Metavolcanics

Superior Province (Archean)

+ Granitic rocks

Gn Granulite and amphibolite facies gneisses

Mafic to ultramafic intrusive rocks

(Archean or Proterozoic, from Geophysics)

— Anomalous Bouguer Gravity

▲▲▲▲ Calculated Gravity

Gravity Model, Density in g/cm^3

Observed Total Magnetic Field

Assumed Regional Magnetic Field

x x x x x Computed Regional Magnetic Field

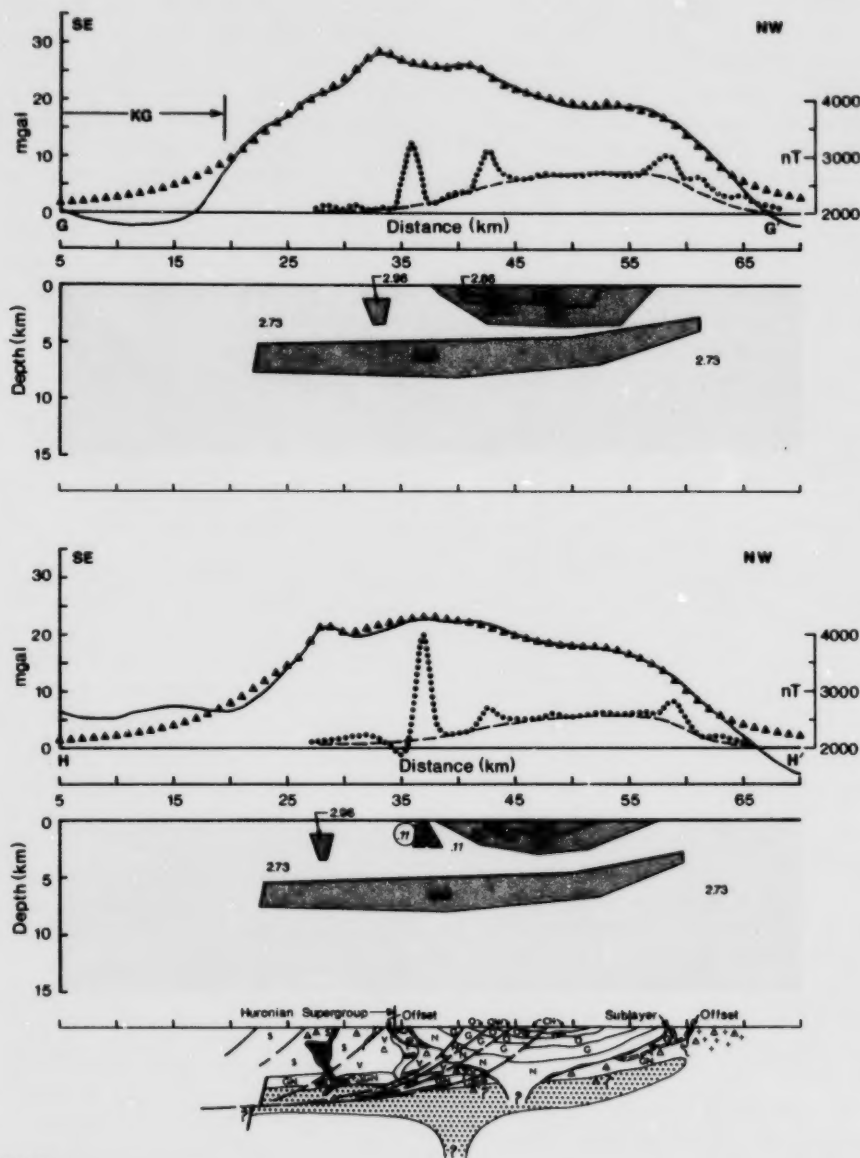
.25 Magnetic Model, Susceptibility in SI

(.25) Magnetic Model, Susceptibility in SI assuming Remanent Magnetization

Thickness in km

KG Killarney Granite

Figure 18.16. Profiles CC' to HH' showing the gravity interpretation consisting of Sudbury gravity anomaly Model B and residual anomalies. Near surface models computed from residual magnetic anomalies on profiles CC' to HH' and regional magnetic model for profile EE' are also shown.



PRECAMBRIAN Southern Province (Early Proterozoic)

SUDBURY STRUCTURE

- Gabbroic rocks (from Geophysics)
- SUDBURY IGNEOUS COMPLEX**
 - ▨ Sublayer (marginal sublayer and offsets)
 - G Upper Zone (granophyre and plagioclase-rich granophyre) and Middle Zone (quartz gabbro)
 - N Lower Zone (norite)
- WHITEWATER GROUP**
 - CH Chelmsford Formation (wacke)
 - OW Onwatin Formation (mudstone)
 - O Onaping Formation (heterolithic and minor monolithic breccia)
- FOOTWALL BRECCIA AND SUDBURY BRECCIA**
 - ▲▲ Sudbury Breccia (pseudotachylite)

GABBROIC INTRUSIVE ROCKS

- Nipissing Gabbro (from Geophysics)

FELSIC INTRUSIVE ROCKS

- CG, MG Proterozoic granitic rocks
- Creighton Pluton, Murray Pluton

HURONIAN SUPERGROUP

- S Arenites, wackes, conglomerates
- V Metavolcanics

Superior Province (Archean)

- + Granitic rocks
- Gn Granulite and amphibolite facies gneisses
- Mafic to ultramafic intrusive rocks (Archean or Proterozoic, from Geophysics)

- Anomalous Bouguer Gravity
- ▲▲▲ Calculated Gravity
- ▨ Gravity Model, Density in g/cm³
- Observed Total Magnetic Field
- Assumed Regional Magnetic Field
- ××× Computed Regional Magnetic Field
- ▨ Magnetic Model, Susceptibility in SI
- ▨ Magnetic Model, Susceptibility in SI assuming Remanent Magnetization
- ▨ Thickness in km
- KG Killarney Granite

Figure 18.16. Profiles CC' to HH' showing the gravity interpretation consisting of Sudbury gravity anomaly Model B and residual anomalies. Near surface models computed from residual magnetic anomalies on profiles CC' to HH' and regional magnetic model for profile EE' are also shown.

a density contrast of about $+0.3 \text{ g/cm}^3$, and a thickness of about 3 km. However, it is not possible, using this simple model, to obtain close fits along both the northern and the southern flanks of the anomaly if the body is kept horizontal. It is clear that the northern side of the body is closer to the surface than the southern side. By constructing a 6-sided polygon instead of a quadrilateral, greater freedom was given to the structure to adjust its shape in order to fit the gravity data. Using a 2½-D interactive algorithm, a good fit to the positive anomaly was obtained along all profiles with the structure shown in Figure 18.16. If Model B (Figure 18.16) is compared with Model A (Figure 18.14), it is obvious that the general shape and form of the 2 models, which started out from very different assumptions, appear similar. The differences are that in Model B (Figure 18.16), there is only a single positive mass, and it appears to be at a shallower depth on the southern side of the Sudbury Structure than the deeper mass of Model A (Figure 18.14). In both Models A and B, the positive mass appears to thicken somewhat near its centre, as though there might be a feeder zone in this vicinity.

Density and Depth Matrix Search: Model B

A matrix search for "best" estimates of the density contrast and the depth of burial (here defined as the depth to the deepest point on the upper surface) of the positive mass of Model B was carried out in the manner previously described, with the result shown in Figure 18.17. Evidently, the best estimate that can be made for the depth of burial of a body having this general shape is between 4 and 6 km. The best estimate for the density contrast is between 0.25 and 0.5 g/cm^3 (see Figure 18.17), which is not significantly different from the values that were obtained for the shallow body in Model A. The modelled positive mass, on average, appears to be about 40 km wide.

In Figure 18.16, the results of computer modelling studies that were carried out on the residual anomalies have been added, as in Figure 18.14.

Both geophysical Models A and B reproduce the Sudbury gravity anomaly with good accuracy. The 2

models are the result of analyzing the Sudbury anomaly in 2 different ways. Although presented here as alternatives, they can probably also be looked upon as end members of a continuous set of possible solutions. It can be stated with some certainty that the general form of the mass which causes this anomaly is broad and sill-like at depth, probably (but less certainly) becoming more steeply dipping toward its northern rim. Although there is some ambiguity about its depth of burial, thickness, and density, these parameters have been estimated within certain confidence limits. The density appears to be between 3.0 and 3.3 g/cm^3 , and the depth is apparently between 5 and 8 km. The geological interpretation of these results will be considered later.

RESIDUAL GRAVITY MODELLING

The residual gravity anomalies (see Figure 18.9) that remain when the Sudbury anomaly is subtracted from the anomalous Bouguer gravity have also been modelled by 2½-D inverse methods. There are 3 gravity anomalies or groups of anomalies which occur within the Sudbury Structure. These anomalies are:

1. the negative gravity anomaly (amplitude -6 mgal) centred close to Fairbank Lake (FL) in Figure 18.9, near the southwestern corner of the Sudbury Igneous Complex
2. the positive linear gravity anomaly (amplitude +2 mgal) over the Onaping Formation on the southern side of the Sudbury Basin
3. the very weak positive anomalies (< 2 mgal) which occur above the Lower Zone of the Sudbury Igneous Complex on several profiles

Outside the Sudbury Structure, the only residual gravity anomalies modelled, are the positive features occurring along a line that is more or less parallel to the southern rim of the Sudbury Igneous Complex. One of these anomalies coincides with an intrusive mass of gabbro-anorthosite near Agnew Lake.

To explain the negative gravity anomaly at Fairbank Lake, which appears in profiles CC' to EE', a density contrast of -0.07 g/cm^3 relative to the background value is needed. Density differences smaller than this fail to give a solution. Using a density difference of -0.07 g/cm^3 , the anomaly can be accounted for by a north-dipping body having a depth extent of about 3 km, whose upper surface coincides with the granophyre outcrop. It is conjectured that this represents a zone of intense fracturing, silicification, and/or thickening of the granophyre by fault repetition.

The positive gravity anomaly over the Onaping Formation can be explained by a north-dipping, mafic body with its top at a depth of 1 km or less and having

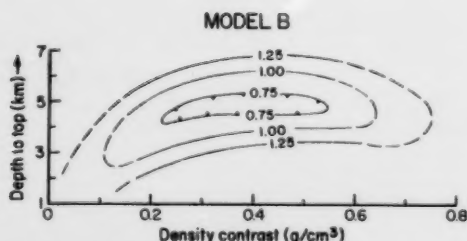


Figure 18.17. Minimized standard deviation (in mgal) between calculated gravity effect (Model B) and inferred values of Sudbury gravity anomaly.

a thickness of about 1 km. Because the anomaly is very weak, it is not feasible to model the density of this body. Its density contrast has been taken as $+0.12 \text{ g/cm}^3$ relative to background, but a higher or lower value would probably do equally well.

The barely perceptible positive anomalies over the Sudbury Igneous Complex suggest bodies which are generally $< 1 \text{ km}$ in thickness, having density contrasts probably smaller than $+0.1 \text{ g/cm}^3$ relative to background, and whose dips are more or less conformable with the general basin structure. These anomalies are obviously related to the norite of the Sudbury Igneous Complex, and a density contrast of $+0.07 \text{ g/cm}^3$ relative to background has been assumed to explain them. The calculated shapes of these slightly positive norite masses are shown in Figures 18.14 and 18.16. The anomalies have very low amplitudes, indicating that the Sudbury Igneous Complex rocks do not develop significantly higher densities or larger thicknesses at depth.

The northern end of profile FF' traverses the Levack Gneiss Complex, which has been modelled as a depth-limited wedge of material having a density contrast of $+0.04 \text{ g/cm}^3$ above the background value.

The strong positive anomalies south of the Sudbury Igneous Complex, referred to as gravity highs VM and L (Figure 18.9), which correlate with the basaltic volcanic rocks of the Elsie Mountain and Stobie Formations, are interpreted as due to gabbroic intrusions. These bodies all seem to occur at a depth of, or slightly greater than, 1 km and to have density contrasts in the range of $+0.2$ to $+0.35 \text{ g/cm}^3$. For modelling purposes, a density contrast of $+0.23 \text{ g/cm}^3$ has been assumed. The calculated depth extent is $< 5 \text{ km}$.

MAGNETIC CHARACTERISTICS OF THE SUDBURY AREA

In the total-field aeromagnetic contour map of the area (Figure 18.2), the Sudbury Structure is clearly outlined by a very distinct elliptical anomaly. This complex magnetic feature has 3 major components, which must originate from 3 quite different sources:

1. A semicontinuous elliptical ring anomaly of large amplitude and small transectional width coincides with the Sudbury Igneous Complex, and appears to be associated with the oxide-rich gabbro phase. This anomaly has a greater amplitude over the South Range of the Complex than over the North Range.
2. A linear anomaly of more moderate amplitude, which is also fairly narrow, lies close to the contact between the Onaping and the Onwatin Formations on the southern side of the Sudbury Basin. It is likely that this anomaly is related to the gabbroic

rocks which intrude the Onwatin Formation near Vermilion Lake (Burkhard O. Dressler, Geologist, Ontario Geological Survey, personal communication, 1983).

3. A broad anomaly, which reaches a maximum amplitude of about $+1000 \text{ nT}$ close to the North Range of the Sudbury Igneous Complex, forms the regional base of the magnetic anomalies of near-surface origin (see Figure 18.18).

This latter anomaly extends beyond the Sudbury Igneous Complex to the northwest into the Levack Gneiss Complex and into the Algonian Granite. The large width of this magnetic feature and the lack of an obvious relationship with the surface geology indicates that it is probably due to rocks which occur at depth.

Regional Magnetic Anomaly

The regional magnetic anomaly can be separated from the magnetic anomalies of shallow origin by a process similar to the one used to separate the Sudbury gravity anomaly from the near-surface residual gravity effects. The magnetic anomalies of near-surface origin are baselevelled, and the local levels are carried smoothly along profiles arranged on an orthogonal (in this case, a 3 by 3 km) grid. The resulting anomaly, designated as the Sudbury magnetic anomaly, is shown as a set of profiles in Figure 18.18, and in contour form in Figure 18.19. Figure 18.19 is very similar to the regional magnetic anomaly that was derived from the same data set by Popelar (1972), which he obtained by

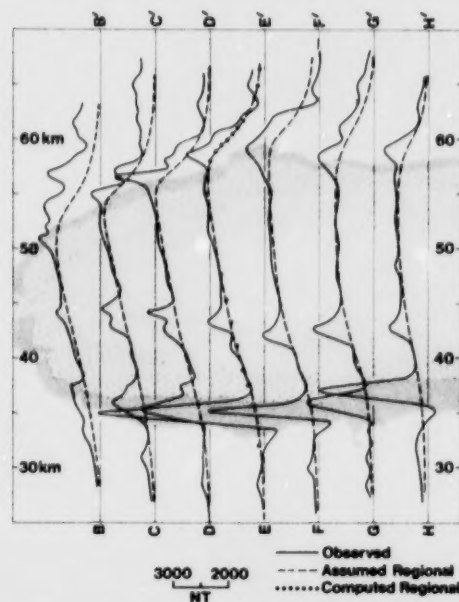


Figure 18.18. Separation of total field magnetic intensity into regional and residual components. Computed regional magnetic anomaly of profile EE' is also shown.

gridding the total-field map at 1 km intervals and by applying a smoothing operator to the gridded values.

A preliminary analysis of the Sudbury magnetic anomaly along profile EE' (see Figures 18.14 and 18.16) indicates that it is caused by a magnetic mass that is tabular in form, at a depth of about 4 km, and dipping approximately 30°S if we assume that the total magnetization vector has the same direction as the earth's magnetic field. In addition to the main magnetic mass, a second smaller body has been postulated to account for the shape of the southern flank of the Sudbury anomaly. The second mass is much smaller, lies at a depth of 8 to 9 km, and may have some remanent magnetization. Because of its large depth of burial, it is difficult to estimate the dip, which appears to be steep. The second body lies close to where a "feeder zone" for the sill-like hidden body has been postulated from the gravity interpretations.

The large, tabular-shaped magnetic body fits reasonably well with the 2 gravity models (see Figures 18.14 and 18.16). Its bulk magnetic susceptibility is calculated to be about 0.25 SI units. If the magnetization was induced entirely by the geomagnetic field and none was remanent, this susceptibility would indicate that the magnetic rocks contain on the average about 7% by volume of magnetite. However, it seems unlikely that the magnetization is not at least partially remanent, and so the rule of thumb relating magnetite content to calculated magnetic susceptibility is probably not very reliable. The small, plate-like body has an

apparent magnetic susceptibility of about $0.8/t$ SI units, where t is the thickness of the body in kilometres. The magnetic properties of this structure cannot be estimated independently of its thickness on account of the large depth of burial.

Residual Magnetic Anomalies

The residual magnetic anomalies that remain after subtracting the regional anomaly (Figure 18.19) from the total magnetic field (Figure 18.2) lie for the most part directly over oxide-rich gabbros of the Sudbury Igneous Complex, and are apparently caused by them. Without exception, these bodies possess remanent magnetizations, and in order to fit the observed anomalies, and at the same time constrain the dips of the fitted bodies to remain close to their measured values, it has been necessary to use total magnetization vectors whose inclinations lie between 70°N and 60°S. Since these directions are the result of adding induced and remanent magnetizations vectorially, it is impossible to determine how much of the magnetization is remanent unless the direction of remanence is known or the induced component can be measured separately. However, the directions of total magnetizations inferred from anomaly analyses are not inconsistent with measurements made by Morris (1980) and by Laroche (1969) on samples taken from the Sudbury Igneous Complex. The modelling results for the residual magnetic anomalies for profiles CC' to HH', within the Sudbury Structure, are shown in Figures 18.14 and

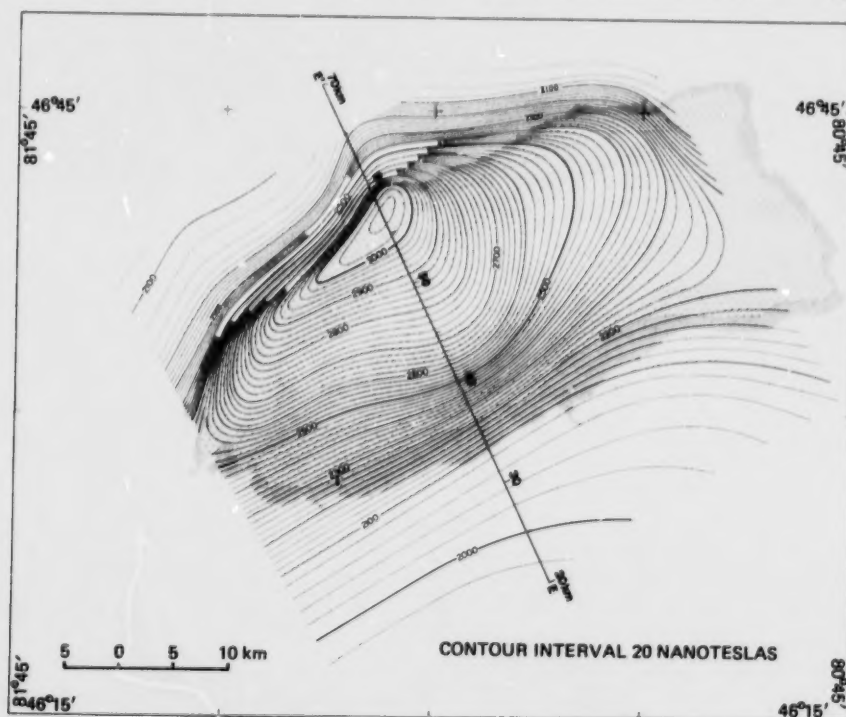


Figure 18.19. Regional magnetic anomaly.

18.16. It is obvious from these studies that most of the Complex rocks are remanently magnetized, and that the ambiguity of polarization versus dip is unresolved. However, there are no major inconsistencies between the gravity and magnetic interpretations, or between the magnetic interpretations and the surface geology, provided that remanent magnetizations are assumed whose directions fall within the range of measured values that have been found among the surface rocks of the Sudbury Igneous Complex.

GEOLOGICAL INTERPRETATION OF GEOPHYSICAL MODELS

Geophysical modelling of the gravity and magnetic data in the Sudbury area leads us to conclude that a large, hidden, dense mass lies beneath the Sudbury Structure. From the shape of the gravity anomaly, it can be said with some certainty that the hidden mass is wide and flat rather than narrow and steep. The shape of its cross-section suggests a broad, funnel-shaped, sill-like body which is similar in form to layered igneous intrusions such as the Muskox and Duluth Complexes (see Table 18.3). The average density is calculated to be between 3.0 and 3.3 g/cm³, which suggests that it is mafic to ultramafic in composition. Except for the northern part, which may be a separate body from the Main Mass, it has no observable magnetic expression, which suggests that the rocks are probably magnesium rich rather than iron rich. A funnel-shaped geometry for the

Sudbury Igneous Complex has also been suggested by Naldrett and Hewins (Chapter 10, this volume) in which the source material has come from the deep-seated body.

The smaller body that lies to the north of this structure, or possibly the northern limb of the structure itself, differs from the Main Mass in that it is quite strongly magnetic. Its strong magnetization and high density suggest that it may contain mafic/ultramafic rocks which are partially serpentinized. Although the geophysical models do not prove any connection between the 2 masses, one might expect some relationship to exist, since both appear to have similar densities and are in close proximity. The vertical distance between their tops, nearly 4 km, almost precludes any hypothesis that the shallow northern body might be a faulted part of the main hidden mass.

The interpretation of the near surface anomalies of the Sudbury Structure indicate that the calculated depths to the base of the granophyre (calculated to be 4.5 km in Model B) is in accord with predictions made from surface geology. Interestingly, it is the same depth extent that was arrived at by Popelar (1972). From its gravity effect, the Sudbury Basin appears to be asymmetric, with the northern limb generally dipping more gently than the southern limb; but on some profiles, the reverse seems to be true. This can be explained without contradicting the surface geology, as described earlier, by changing the relative thicknesses of the granophyre and the Onaping Formation.

TABLE 18.3: A COMPARISON OF SUDBURY GRAVITY ANOMALY WITH OTHER LAYERED INTRUSIONS.

NAME	AERIAL EXTENT km ²	AREA BASED ON GRAVITY km ²	ESTIMATED THICKNESS km	GRAVITY EFFECT mgal	ESTIMATED DENSITY g/cm ³	MAJOR ROCK TYPE	REFERENCES
Stillwater (U.S.A.)	194 (exposed only)	4400 +	5-8.3	+ 40	2.87-3.15	Noritic variety of gabbro	Hess (1960) Bonini (1982)
Muscox (Canada)	1515	3051	6	+ 28 to + 60	2.7-3.2	Mainly dunite with minor pyroxenite and gabbro	Hornal (1968) Irvine and Smith (1967) Irvine (1970)
Bushveld (S.A.)	66 000	?	5	+ 50	3.08	Gabbro with pyroxenite, granophyre, and granite	Hattingh (1980)
Duluth (U.S.A.)	7680	?	20	+ 52 to + 70	2.90	Gabbro, troctolite, anorthosite	Davidson (1972) Bonnichsen (1972) Ferderer (1982)
Sudbury (Canada)	1620	2400	3-4	+ 30	3.05-3.2	Gabbro, norite, granophyre	this paper

The negative residual gravity anomaly (FL) near Fairbank Lake (Figure 18.19) is certainly related to the granophyre which outcrops in this vicinity. Since the anomaly falls within the Upper Zone of the Sudbury Igneous Complex, it suggests that the granophyre in that area is lighter than it is elsewhere by about 0.04 g/cm^3 . Since the Fairbank Lake area is the site of an unusually high concentration of major faults, it is conjectured that the lowered density may be due to heavy fracturing and/or silicification of the granophyre, with thickening due to fault repetition.

Interpreted geological cross-sections based on the gravity and magnetic modelling, together with surface geology, are given in Figures 18.14 and 18.16.

SUMMARY AND CONCLUSIONS

A study of the gravity and magnetic fields in the Sudbury area has led to a number of new concepts relating to the Sudbury Structure, its geological setting, and evolution. The Sudbury Structure occurs within an arcuate zone of dense rocks that extends over a distance of nearly 350 km from Elliot Lake through Sudbury and Temagami to Englehart. The Sudbury gravity and magnetic anomalies are only one of several such anomaly pairs that lie along this zone.

The Sudbury Structure occurs within a positive elliptical gravity anomaly of $+30 \text{ mgal}$ that is significantly broader than the Structure itself, with horizontal dimensions approximately 60 by 40 km. The anomaly is too broad and too intense to be caused by any downward extension of the rocks of the Sudbury Structure as mapped at surface. These exposed rocks are not sufficiently dense or voluminous to produce the observed gravity effect. Similarly, the magnetic anomalies over Sudbury cannot be attributed solely to the rocks of the Sudbury Structure.

It is proposed that the gravity and magnetic anomalies at Sudbury are attributable mainly to a hidden body or bodies of mafic/ultramafic rocks that lie beneath the Sudbury Igneous Complex. This body is essentially sill-like in form and subhorizontal in attitude. Its southern part is approximately 2 to 4 km thick, lies at a depth of about 5 to 8 km, and extends beyond the boundaries of the Complex in all directions. The northern part of this mass (or a separate, smaller body) is strongly magnetic and lies at a relatively shallow depth of 2 to 5 km.

The average density (3.0 to 3.3 g/cm^3) of the hidden body (or bodies) indicates that it (they) have a mafic or ultramafic composition, possibly consisting of rocks such as anorthositic gabbro, olivine gabbro, or dunite. The hidden body could be a large, sill-like, funnel-shaped, layered mafic/ultramafic intrusion

similar to other layered intrusions such as the Muskox and Duluth Complexes.

The gravity and magnetic modelling suggests that the Sudbury Structure itself is basin-like in shape. The calculations suggest that the Whitewater Group and the granophyre form an asymmetric basin with a maximum thickness of 4 to 5 km (to the base of the granophyre). Within the Onaping Formation, on the southern side of the basin, mafic intrusions having a density of about 2.85 g/cm^3 have been modelled, which may be related either to the Sudbury Igneous Complex or to the hidden body, or to both.

The relationship of the Sudbury Igneous Complex to the hidden body is not clear. The 2 units are in close proximity, and they may be in contact. If, as is indicated by the gravity and magnetic modelling, the hidden body consists of mafic and ultramafic rocks, then it represents a likely source for some of the inclusions in the Sublayer of the Sudbury Igneous Complex. This would imply that the hidden complex is somewhat older than the Sudbury Igneous Complex and may represent one more manifestation of magmatic activity along a zone of major crustal dislocation-activity that began with Huronian volcanism in the Early Proterozoic and culminated with emplacement of the Sudbury Igneous Complex some 600 Ma later.

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CHAPTER 19

Paleomagnetic Constraints on the Magmatic, Tectonic, and Metamorphic Evolution of the Sudbury Basin Region

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ABSTRACT

The Sudbury Igneous Complex consists of 3 components; the Main Mass, the Offset Dikes, and the Sub-layer. Paleomagnetic studies on over 2000 samples from these 3 components indicate the Sudbury Region was an active part of the Earth's crust from at least 2200 Ma to approximately 1250 Ma.

The Sudbury Igneous Complex contains the record of at least 4 (and possibly 5) temporally distinct periods of intrusion: norite, granophyre (first phase),

Onwatin-Onaping sills, granophyre (second phase), and the Middle Zone quartz gabbro. During each period of intrusion, magma was emplaced into each component of the Sudbury Igneous Complex.

Over the same period of time, there is evidence for 4 deformation events: a pre-Nipissing event, a post-Nipissing pre-norite event, a syn-norite event, and a post-norite pre-second phase granophyre event.

Three periods of nickel sulphide mineralization have been recognized; 2 appear to be genetically related to and intimately associated with igneous intru-

sions, while the third or youngest period of sulphide emplacement appears to be epigenetic.

The Sudbury Igneous Complex contains the record of multiple intrusion deformation and mineralization events. All of these point to geological processes active over a broad period of time and not to a single event. The geology of the Sudbury area exhibits many temporal and lithological similarities to those of the Penokean Fold Belt in Michigan and Wisconsin, U.S.A. No special pleading has been invoked for a meteoritic event in these areas. If such a meteorite event occurred in the Sudbury region, it probably formed only a small part of a long and complex geological history.

INTRODUCTION

The Sudbury Igneous Complex comprises a number of interrelated intrusive units. The Main Mass of the Complex includes: Lower, Middle, and Upper Zones. In the Upper Zone, Peredery and Naldrett (1975) have recognized 2 distinct phases called the differentiate granophyre and the plagioclase-rich granophyre. The Offset Dikes are a series of dike-like structures that radiate out from, or are sub-parallel to, the base of the Main Mass. The Sublayer is a discontinuous unit that occurs between the Main Mass and the Footwall rocks.

Many aspects of the magmatic relationships of these units are imperfectly known. For example, there are ambiguous answers to the following questions:

1. Did the Main Mass differentiate *in situ*, or is it the result of a number of separate intrusive pulses?
2. What are the exact temporal and spatial relationships of the Offset Dikes to the Main Mass?
3. What is the significance of the Sublayer, and does it predate, or postdate (or both?) the Main Mass?

In summation, these questions ask if we can document the magmatic evolution of the Complex.

The Sudbury Basin presently has the configuration of a slightly flattened ellipsoid (Figure 19.1). The East and South Ranges have steeper dips than the other Ranges. What part is original or the result of subse-

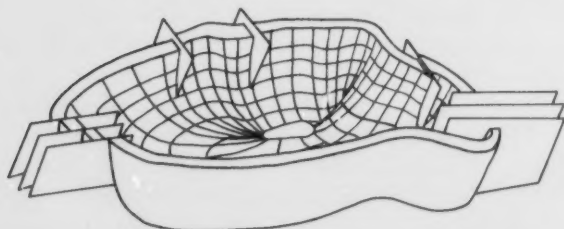


Figure 19.1. Diagrammatic representation of the geometry of the present outer surface of the Sudbury Basin.

quent deformation, is open to question. It has been suggested that the Sudbury Structure is the signature of a meteorite impact. Dietz (1964), and later French (1970), hypothesized that an originally circular structure was deformed at some later date into the elongate basin that we observe today. However, as noted by Card and Hutchinson (1972) "folding of the White-water rocks is gentle, implying relatively little crustal shortening, whereas the change in plan from a circular to an elliptical shape for the Sudbury (Igneous Complex) implies relatively great shortening along the minor axis of the structure". Evidence of such a major crustal shortening should also be evident in the rocks immediately south of the Sudbury Basin. Yet, the timing and extent of the total deformation history of this region has also been the subject of recent discussion. At one extreme, Brocoum and Dalziel (1974) contended that all the structures observed in the Sudbury Basin, and the adjacent Southern and Grenville Provinces, were caused by a single post-Sudbury Igneous Complex tectono-metamorphic event. In contrast, Card (1979) claimed that there is geological evidence for 4 temporally distinct deformational events in this same region. Only 1 of these events is considered to postdate the formation of the Sudbury Structure. Thus, Brocoum and Dalziel (1974) and Card (1979) apparently agreed that there was only 1 post Main Mass event. It is the extent of this event that is in dispute.

Paleomagnetism may serve to answer the following questions concerning the tectonic evolution of the Sudbury Structure.

1. How many folding events have there been in the region as a whole since the deposition of the Huronian sediments?
2. What is the distribution spatially and temporally of the different deformation events?
3. What was the timing of these events relative to the intrusion of the Main Mass of the Complex?

A temporal setting for the emplacement of the mineral deposits can only be imperfectly elucidated when evident uncertainties exist in understanding the evolution of the Sudbury Structure as a whole. Of the many theories that have been advanced to explain the genesis of the Sudbury deposits, the following have been the subject of most discussion:

1. syngenetic magmatic segregation resulting from either multiple intrusion at depth, or differentiation *in situ*
2. epigenetic introduction, with deposition related to post-intrusive mineral-rich fluids
3. meteorite impact, where the sulphide minerals are derived directly from the bolide

In summary, to what extent can paleomagnetism be used to establish regional patterns for the timing and genesis of the mineral deposits?

The importance of paleomagnetism as a tool for the unravelling of the geologic history of an area is because of its unique property to record specific vector orientations that relate to different geological events. This is the only potential method of documenting the sense and magnitude, and in certain special situations, the timing of relative rotations between rock units. In addition, a time-dependant shift in the orientation of the magnetic vector relative to the sampling area (polar wander/continental drift) permits the determination of the time of remanence acquisition. The multiple recording abilities of certain rock units by magnetic overprinting can provide documentation of thermal and chemical pulses since their formation. Paleomagnetic studies thus can be used as a survey tool to support detailed geological examination, and can often help to unravel some of the complexities of the magmatic, metamorphic, and tectonic evolution of a region.

PREVIOUS PALEOMAGNETIC STUDIES AND CONVENTIONS

Previous paleomagnetic studies of the Sudbury Igneous Complex (Hood 1961; Sopher 1963; Larochelle 1969) all recognized a significant directional discordance ($\sim 40^\circ$) between samples from the North and South Ranges, indicating tectonic rotation of one range relative to the other. It was Larochelle (1969) who noted that the "paleomagnetic picture...now appears to be more complex than originally envisioned". Later, an attempt at interpreting the then available data in a regional context suggested tectonic rotation of both the North and South Ranges (Irving and Lapointe 1975). In this compilation of paleomagnetic data, the author has used all results published up to the time of writing in early 1983. For the Sudbury Basin, the author has used data that was produced over the period from 1978 to 1981; this supercedes all other data sets from the Basin (Morris 1980, 1981a, 1982a, 1982b, 1982c, 1982d).

For information on the paleomagnetic methodology used, and on the statistical details of each investigation that is pertinent to the evolution of the Sudbury Igneous Complex, the reader is referred to the original publications. Herein, the author presents the detailed conclusions of each of these studies as they relate to the paleomagnetic constraints that may be imposed on evolutionary models. Crucial to these constraints is the application of geological tests of remanence acquisition age. The 2 "conclusive" tests that are commonly applied in this study are the "contact test" and the "fold test".

The *contact test*, which is by far the most powerful of acquisition age tests, compares the remanence directions present in an intrusion, its thermal aureole,

and the surrounding unaltered country rock. A *positive contact test* provides absolute evidence that the remanence signature observed in the intrusion dates exactly the time that the intrusion cooled below the Curie Points of the magnetic carriers, usually around 500° to 700°C .

The *fold test* compares the grouping of the remanence directions from different parts of the limbs of a folded unit. In this test, the grouping of the directions calculated, when referenced to the present horizontal plane, is compared to the grouping of the directions after they have been rotated to an original horizontal plane, that is, by rotating the beds back to a dip of 0° . If there is a statistically significant increase in the precision of the grouping, then one can be assured that the remanence was acquired prior to the time of folding. An important restriction on this test is the age of folding relative to the age of formation of the rock unit. If, for example, there were 200 Ma between the time of sediment deposition and its subsequent deformation, then a positive *fold test* would restrict initial remanence acquisition only to sometime in the 200 Ma period.

The chronology of acquisition of remanence directions employed in the analysis reported here was established using, where possible, the *contact test* and the *fold test*. Where these tests were inapplicable, then a tentative chronology was established using the degree of alteration, the areal distribution of the remanence direction relative to a specific rock unit, and the relationship of the remanence direction to local geological features. For remanence directions obtained from the norite and the granophyre, particular importance has been placed on the constraints imposed by geometrical considerations of geologically feasible correlations between the remanence directions of different limbs of the Sudbury Basin. That is, the correct correlation of remanence directions is taken to be that which minimizes the rotations required to equate directions which were acquired contemporaneously, but which presently exhibit different orientations due to tilting of the different limbs after remanence acquisition.

Remanence directions have been used throughout this paper to describe the individual magnetic components in the different rock units of the Sudbury Igneous Complex. All the sampling sites are in close proximity to each other, and therefore, it is not necessary to use pole calculations for valid comparisons of the magnetic components. Some of the different rock units have similar remanence components. To facilitate understanding of the text, a 3-digit convention has been adopted, to:

1. identify the individual rock unit (N is Norite, M is Granophyre, O is Offset Dike, S is Sublayer)
2. identify the individual remanence component di-

rections (1, 2, 3 are variable from area to area within the Sudbury Igneous Complex, 4 is northwest positive inclination, 6 is north-northeast steep positive inclination, 7 is east-southeasterly shallow positive inclination, and 8 is due west steep positive inclination)

- identify the part of the Sudbury Structure from which the samples were collected (E is East Range, N is North Range, S is South Range, and W is West Range). For example, N8E would be a westerly directed steep positive inclination component from a norite outcrop on the East Range, and S6S would be a steep positively inclined north-northeast vector from the Sublayer of the South Range. When referred to in the context of the Basin as a whole, individual remanence directions are identified by the term "Types", for example, Type 8 direction.

DISCUSSION

Magmatic History of the Sudbury Igneous Complex

Of the 7 remanence directions from the Sudbury Igneous Complex listed in Table 19.1, 3 (Type 1, Type 2, and Type 6) are supported by fully executed positive contact tests for remanence age. These directions then

must be recording 3 temporally distinct intrusive pulses.

Good evidence suggests that the Type 8 remanence direction also records a separate intrusive event even though it is not supported by a positive *contact test*. First, the Foy Offset Dike in Hess Township carries the O8N direction residing in both magnetite and hematite in barren quartz diorite adjacent to the contact (Morris and Pay 1981). A sulphide-rich zone at the centre of the Foy Offset Dike in this same outcrop has partly the same remanence directions, but with lower pyrrhotite blocking temperatures. Hematite, magnetite, and pyrrhotite all recording the same remanence direction can only be explained by cooling from some high temperature ($>650^{\circ}\text{C}$). As the Foy Offset Dike does not exhibit mineralogical expression of high grade metamorphism, the most logical explanation is that the O8 direction is recording the remanence direction in effect at the time of magma intrusion. A small dike that cross-cuts the centre of this Offset Dike and this sulphide zone, records only the O6N direction. This implies that O8N preceded O6N. Second, the O8N direction is found in the "baked zone" of the Foy Offset Dike near Nickel Lake (Morris 1982b), but not in the immediately adjacent Offset Dike or in the more distant country rock. One explanation of this observation is the presence of an unexposed intrusive phase

TABLE 19.1: SUMMARY OF REMANENCE DIRECTIONS FROM THE SUDBURY IGNEOUS COMPLEX.

NORITE							
Range	N1	N2	N5/N8	N6	N3	N4	N7
South	156,43	> 192,69			204,38		
North	*316,69*			017,59	209,25	> 327,31	109,30
East	084,37	087,78		024,66	211,30		
West	273,45	283,73			219,37		
GRANOPHYRE							
Range	M1	M2	M5/M8	M6	M3	M4	M7
South		203,78	> 268,63	> 033,69		> 329,24	
North		*329,68*	> 285,70	> 025,67		325,23	102,32
East		098,71	269,77	037,71		> 315,42	
West			274,68	041,70		327,30	
OFFSETS							
Range	O1	O2	O5/O8	O6	O3	O4	O7
South	158,51	202,73	270,74	028,67	213,39	319,27	
North	*341,61*		> 273,69	> *029,69*	206,38	333,32	
West					195,43	311,28	
SUBLAYER							
Range	S1	S2	S5/S8	S6	S3	S4	S7
South	165,50	186,73	269,66	046,54	212,26	326,42	110,49
East	090,29	104,82	305,80	036,55		319,28	123,39

Notes:

- Offset Dikes include: the Copper Cliff, Worthington, Kirkwood, Manchester, and the Frood-Stobie Offset Dikes for the South Range; Foy-Bowell Township, Foy-Foy Township, Foy-Hess Township, and Milnet for the North Range. Ministic for the West Range.
- The directions marked by the * * symbols are supported by positive contact tests and, therefore, must be dating a specific intrusive event.
- The > symbol indicates the relative ages of the remanence directions where they have been defined by contact tests or other supportive geological relationships.

along the margin of the Foy Offset Dike. Third, the Type 8 direction is the most commonly observed direction in the granophyre where it is usually characterized by remanence phases with unblocking temperatures as high as 670°C. The Type 8 direction is recording either a metamorphic event or a separate intrusive event. Faced with the same options, Gibbons and McNutt (1972, 1975a) initially favoured the intrusive option, but later preferred the metamorphic option. The paleomagnetic data definitely favour the intrusive option. Many specimens from the norite that underlies the granophyre, and the Onaping Formation, which overlies the granophyre, have unblocking temperatures that are lower than those found in specimens of granophyre. Yet, there is only limited evidence of the Type 8 direction in either the norite or the Onaping Formation (Table 19.1). A metamorphic model requires the unlikely scenario of a regional metamorphic event that was somehow basin wide in the granophyre, yet highly localised in the Offset Dikes.

Direct implication of the *contact test* evidence is that each unit of the Sudbury Igneous Complex (the Main Mass, the Offset Dike, and the Sublayer) contains the geological record of at least 4 temporally distinct intrusive pulses. Figure 19.2 shows that each intrusion-related remanence type (1, 2, 8, and 6) has identical orientation in all rock units in any one particular Range of the Sudbury Structure. With each intrusive pulse, magma was contemporaneously emplaced in the Main Mass, the Offset Dike, and the Sublayer. In the Main Mass, these 4 phases correspond to the norite; the granophyre, first phase; the granophyre, second phase; and the Middle Zone quartz gabbro. The temporal correlatives of rock units in the Main Mass may have different lithologies in the Sublayer, or Offset Dikes. Magma could have been derived from chemically distinct regions of a large magma chamber. For example, the equivalent of the quartz diorite Offset Dike is possibly the plagioclase-rich granophyre of the Main Mass. The paleomagnetic data also suggest that the unit commonly referred to as the Sublayer is probably a composite of the 4 intrusive events; the norite-Footwall contact acting as a conduit along which subsequent magma pulses were emplaced. This hypothesis serves to explain the confusing contact relationships between the Sublayer and the norite (Naldrett *et al.* 1972), and the multiple cross-cutting relationships that are commonly observed in the Offset Dike. It also suggests that the contacts between the individual units of the Main Mass may be much sharper than has been previously thought (Naldrett *et al.* 1970).

Tectonic History of the Sudbury Igneous Complex

Seven remanence types are listed in Table 19.1; only

the Type 1 and Type 2 directions show significant systematic angular differences between different Ranges of the Basin (see Figure 19.2). For most of the other remanence types, the angular differences between Ranges are within the errors associated with the mean directions representative of a particular Range, and/or the direction determinations representing the different rock units from any one Range do not show any systematic bias relative to directional determinations from the remainder of the Sudbury Igneous Complex. The exception may be the Type 3 directions. Where detected solely in the norite (Lower Zone of the Sudbury Igneous Complex), Morris (1980, Figure 10) has shown that the Type 3 directions exhibit a significant systematic difference between the South Range and all other Ranges of the Sudbury Igneous Complex. In Figure 19.2, the Type 3 direction from the Sublayer of the South Range does not appear to support this observation. The norite, however, is taken as defining the correct angular difference because:

1. The Offset Dike O3S direction, which is based on data from over 12 sites, more closely agrees in inclination with the South Range norite N3S direction that is based on data from over 15 sites.
2. The Sublayer S3S direction is based on data from only 2 sites.
3. The directions from the sulphide-rich Sublayer are commonly divergent so that site means are often poorly defined (for example, see the Type 6 direction in Figure 19.2).

In the following section, geologically reasonable tilt corrections are applied to the paleomagnetic data to define the sequence of tectonic and metamorphic events that formed the Sudbury Basin. Taking the simplest possible approach, it can be assumed that the largest angular difference records the largest degree of tectonic rotation. The correct equivalence of remanence directions is taken to be that which minimizes the total amount of tectonic rotation. Following Morris (1980), and as argued above, the smallest angular difference is shown by the N3S direction. Compatibility of the norite directions between the South and other Ranges requires a rotation of the South Range, by ~10° about an axis striking 130°. This strike is plausible because it is perpendicular to many of the major faults that cross the Sudbury Basin. Estimated vertical motion on these faults ranges from 1.6 km (Card and Hutchison 1972) to 6.4 km (Naldrett *et al.* 1970).

These directions should be corrected for the rotations documented by the Type 3 directions before the Type 2 direction is analyzed for evidence of tectonic rotation. After this correction, the directions from the different Ranges still maintain statistically distinct groupings (see Figure 19.2). If the contemporaneity of remanence acquisition for the Type 2 directions is assumed, these angular differences must be recording independent rotations of each Range of the Sudbury

Basin. Each Range is rotated about its average local strike to generate a small circle tilt correction path on the stereonet. The intersection point of the small circle paths defines the true remanence direction at the time of remanence acquisition (Table 19.2). The arc length of the small circle between the observed remanence direction and the intersection point is a measure of the degree of rotation that segment has undergone since remanence acquisition. Applying these rotations and calculating the mean direction, constitutes a *fold test* positive at the 99% confidence level. The rotations defined by the Type 2 directions are 26°, 32°, 12°, and 0 to 5° for the East, South, North, and West Ranges, respectively (Morris 1981a). All rotations are inward toward the centre of the Sudbury Basin. This suggests that the Sudbury Structure had the form of a near symmetrical basin having uniform dips of about 40° to 50° on all Ranges at this stage in its evolution.

A similar analysis can be applied to the Type 1 remanence directions. Figure 19.2 shows that the small circle rotation paths associated with the Type 1 direction define a fairly precise intersection point even after

correcting for the rotations associated with the Type 2 and Type 3 directions. The rotations recorded by the Type 1 directions, which must predate the acquisition of the Type 2 directions, are 35°, 23°, and 42° for the East, South, and West Ranges respectively. The average rotation for the North Range is 12°, but individual localities may have been rotated from 0° to 20°. Again, these rotations represent a *fold test* positive at the 99% confidence level.

If the norite (Lower Zone) was intruded soon after the Sudbury Basin began to form, then the initial configuration of the Basin is defined by the geometry of the norite at the time of Type 1 remanence acquisition. At this time, the Basin was an open syncline plunging gently to the southwest. Both the North and the South Ranges were dipping inward at around 20° to 30°, the East Range was dipping at about 15° to the southwest, and the West Range was subhorizontal. This is exactly equivalent to the geometry of the Basin inferred from sedimentological studies (Cantin and Walker 1972; Rousell 1972).

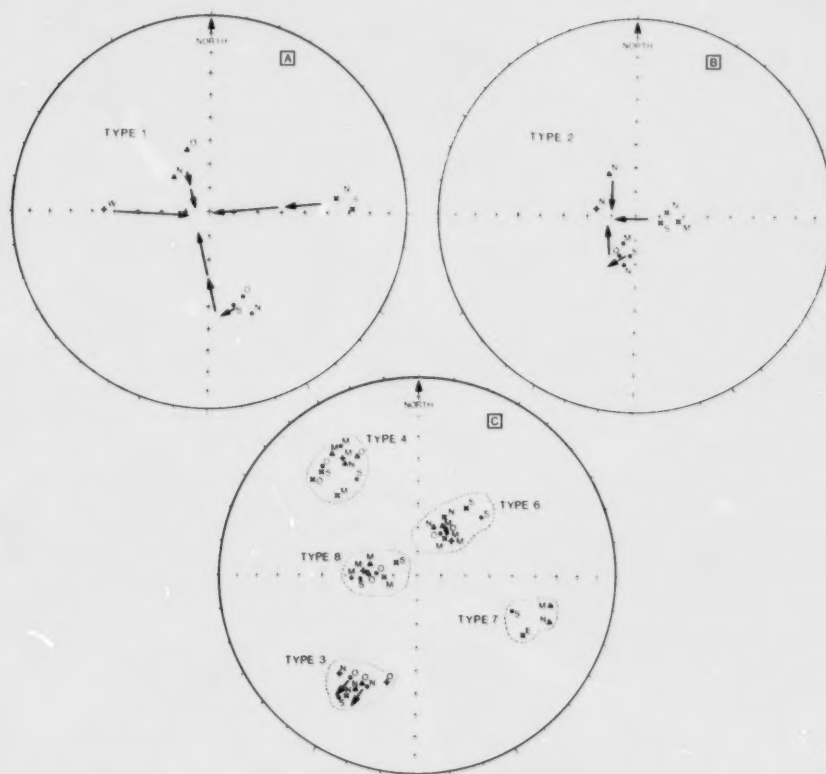


Figure 19.2. Equal angle stereonet showing the distribution of the remanence directions listed in Table 19.1. Directions from the individual Ranges of the Basin are: North Range, East Range, South Range, West Range, and the different rock types sampled are N-Norite, M-Granophyre, O-Offset Dike, S-Sublayer. The younger magnetizations, Types 4, 6, 8, and 7, do not show any directional differences between the separate Ranges. The Type 1 and 2 directions and possibly the Type 3 direction (see text) show angular differences and hence are recording deformation of the Basin. The arrows indicate the trajectory of the remanence directions upon progressive tilt correction.

Geometrical History of the Sudbury Igneous Complex

Any change in the strike of an individual element of the Sudbury Igneous Complex from its initial configuration at the time of remanence acquisition should be reflected by a similar change in remanence declination. The Basin is assumed to have been originally circular. If this is changed to an elliptical shape, and the continuity of the basin perimeter is not disrupted by faulting or buckling, then different segments would undergo different degrees of rotation. Segments parallel and perpendicular to the maximum axis of flattening can be translated to their new position with only minimal rotation (Figure 19.3a). Segments which start at 45° to the plane of flattening may undergo up to 45° rotation. As flattening progresses, greater and greater rotations are possible. Significant deformation of any part of the Basin should be shown by the presence of locally aberrant remanence directions.

Two "areas" exist that can be paleomagnetically tested to see if the Sudbury Igneous Complex originally had a circular plan. First, the remanence direction variations can be analyzed for some particular segment of the Basin. As shown in Figure 19.3a, any flattening produces a diagnostic pattern in the remanence directions. The systematic change in strike from one side of the Basin to the other will always be the opposite to the change in remanence declination directions. Paleomagnetically, this flattening can be tested

by calculating the representative mean direction for some segment of the Basin. The tightness of grouping of the individual remanence directions as reflected in the Fisher (1953) precision parameter would be significantly reduced if flattening had been important. Other curvatures can be allowed, and the changes in the Fisher precision parameter can be calculated. Thus, the best fitting plan can be determined. Second, the remanence directions from each side of a sharp bend in the present plan can be compared. If the present plan approximates the original configuration, and subsequent deformation has involved only simple single axis tilting, then rotation about the present strike should produce the best match of corrected remanence directions. Alternatively, if the present configuration does not approximate the original configuration, then rotation(s) about some axis (axes) other than the present strike should produce the highest Fisher precision.

The North Range fulfils the criteria for the first type of test. In this segment, both the declination and the geological strike change in a clockwise manner around the Basin. Thus, the data do not show the geological strike-remanence declination relationship that would be typical of a deformed circle. Testing other curvatures does not produce any significant improvement in the overall precision. The present configuration, then, best describes the shape of this part of the Sudbury Igneous Complex at the time of norite intrusion. This is not particularly surprising as some authors (Rousell 1975) consider the North Range to be

TABLE 19.2: SUMMARY OF MEAN REMANENCE DIRECTIONS AND POLES FOR THE SUDBURY IGNEOUS COMPLEX.

Type	D,I DEGREES	N	R	k	α_{95} DEGREES	LAT., LONG. DEGREES
1*	268.82	8	7.93	95	6	44N, 257E
2*	276.72	9	8.90	79	6	40N, 234E
3*	209.31	8	7.89	62	7	22N, 069E
8	277.73	9	8.92	99	5	42N, 235E
6	032.65	10	9.92	119	4	68N, 356E
4	323.31	10	9.89	85	5	47N, 157E
7	111.38	4	3.94	54	13	25N, 160E

Event: NORITE INTRUSION
Event: GRANOPHYRE - 1 INTRUSION
Event: MINERALIZATION/INTRUSION ?
Event: GRANOPHYRE - 2 INTRUSION AND MINERALIZATION
Event: DIKE INTRUSION - MIDDLE ZONE QUARTZ DIORITE
Event: MINERALIZATION
Event: GRENVILLE FRONT METAMORPHISM

Notes:

- Directions marked by * are quoted after tilt correction as discussed in the text.
- D and I are the declination and inclination respectively, of the mean remanence vector
- R is the vector resultant, k the precision parameter, and α_{95} the radius of the cone of 95% confidence of Fisher (1953).

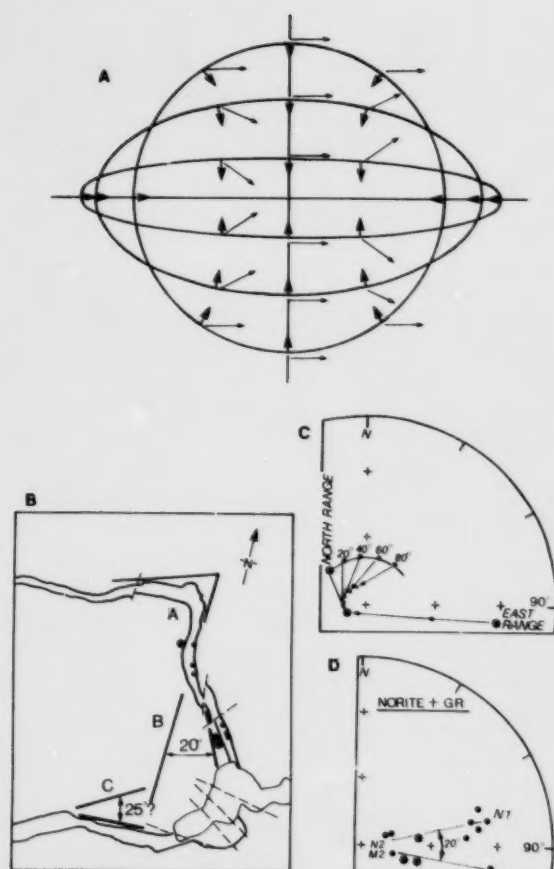


Figure 19.3a. Maintaining the same circumferential length while deforming a circle into a gradually more and more elongate ellipse produces different strike rotations with the dip direction indicated by the short thick arrow at different points around the perimeter of the circle. Assuming non-penetrative deformation, any amount of flattening also produces rotation of the local remanence direction which is represented by the long thin arrow. Detection of the degree of flattening can be easily documented by determining the curvature of some Basin segment which optimizes the tightness in grouping of remanence directions from that segment. If the paleomagnetically preferred curvature differs from the present curvature, then flattening is present.

Figure 19.3b. Diagrammatic representation of the present angular relationships of the East, North, and South Ranges, and the possible rotations they have undergone during deformation.

Figure 19.3c. Comparison of the tilt-corrected remanence directions from the East and North Ranges upon allowing different strike orientations for the North Range. Increasing the inter-Range angle by more than 40° causes the remanence directions from the 2 Ranges to become statistically distinct.

Figure 19.3d. Comparison of *in situ* remanence directions from the norite and the granophyre from different segments of the East Range. This analysis indicates rotation of the southern part of the East Range.

the only surviving undeformed segment of an original circular Basin. If the North Range is a true sector of the original structure, then the latter had to have an original diameter of at least 150 km. All the deformation of this circle would have had to be accommodated by the East, West, and South Ranges. This could only be achieved by large-scale buckling of the norite if the total length of the original circumference is preserved.

The sharp bend at the northeastern corner of the Sudbury Basin (Figure 19.3b) provides an excellent example of the second type of test. Figure 19.3c compares the tilt correction path for the East Range data with the immediately adjacent North Range data. The mean direction of the North Range after tilt correction was calculated for a gradually increasing angle between the North and East Ranges. If the inter-Range angle is increased, the tilt corrected North Range direction is seen to become gradually more divergent from the tilt corrected East Range direction. The application of a paleomagnetic fold test to this analysis suggests that a rotation of only 40° between the 2 limbs is permissible before a statistically significant reduction in the overall Fisher precision parameter occurs. Again, the paleomagnetic data indicate that the present configuration best describes the shape of this zone at the time of norite intrusion.

Both the East and South Ranges show angular changes in strike direction (Figure 19.3b see A, B, and C). In both cases, these changes become more pronounced toward the southeastern corner of the Basin. The sampling of both the norite and the granophyre from the East Range, permits a test of the age of these suspected rotations to be made. By far the most useful data are the N1E directions of the norite. These remanence directions are shallowly inclined, therefore, the measured estimate of their remanence declination can be more accurately defined, and any statistical tests as a result have narrower windows for specified degrees of probability. Remanence directions from the more northerly (north-trending) segment of the East Range have declinations of 100° , whereas the more southerly (northwest-trending) segment have declinations of 075° to 080° . Therefore, the 2 segments have undergone approximately 20° of relative rotation. This rotation is in the correct sense and magnitude to bring the southern segment of the East Range back into alignment with the north segment. The preferred original configuration for the East Range is a simple north-south strike.

No paleomagnetic data are presently available to investigate possible rotations of the eastern part of the South Range (Figure 19.3b). Tentative support for rotation of this area can be found by taking an overall view of the Basin structure. The maintenance of the sharp bend at the northeastern corner of the Basin as discussed above, and the combination of it with a north-south oriented East Range, suggest that the east-

ern limit of the South Range has been displaced by some distance to the east. Evidence has been given for block fault rotation of the South Range relative to the rest of the Sudbury Igneous Complex (Morris 1980). If the East and South Range are brought into agreement at the southeastern corner, and if the South Range is given a uniform southwest-trending strike, a length difference that is exactly equivalent to the total displacements on the faults at the southwestern corner of the Basin will result. This indicates that not only has there been rotation, but that some lateral translation on these faults has also occurred.

A simple elliptical form appears to best describe the original form of the Sudbury Igneous Complex. No evidence exists to suggest that the Basin was deformed from an originally circular form, at least that is, subsequent to the intrusion of the norite from which most of the evidence was gathered. Tectonic rotations on the East and South Ranges are the result of post-norite tectonic deformation of an original elliptical structure. The rotations about a vertical axis documented in this analysis are probably temporal equivalents of the rotations about the horizontal axis that are recorded by the Type 2 magnetizations of the South and East Ranges. Deformation of a fixed circumference of the norite ellipse to a slightly smaller ellipse was accommodated by buckling and tilting, especially in the southeastern corner of the Basin.

Temporal History of the Sudbury Igneous Complex

The positive *contact tests* and *fold tests* partly define an acquisition sequence for the 7 remanence directions listed in Table 19.1. Together with constraints imposed by the areal distribution of particular remanence directions with respect to different rock units, the paleomagnetic evidence provides a relative chronology of magmatic events involved in the formation of the Sudbury Igneous Complex.

The oldest magnetization, the Type 1 direction, is intimately associated with the formation of the Lower Zone (the norite) of the Sudbury Igneous Complex. The Type 2 direction, the next oldest remanence direction, is found in both the granophyre and the norite. Where present in the norite, especially in the South Range, the Type 2 direction is clearly related to metamorphic overprinting. This event is recorded by the lower equilibrium temperatures reported by Gasparinni and Naldrett (1972) for magnetite in the South Range norite. Type 2 then dates the first phase of granophyre intrusion. Whether this intrusive phase is the differentiate granophyre or the plagioclase-rich granophyre, should be resolved by a thorough petrological examination of the available samples (Morris 1981a). As shown in Table 19.2, the mean direction after tilt correction associated with the first phase of grano-

phyre intrusion is statistically identical to the tilt-corrected norite Type 2 direction. The best estimate for the age of remanence direction, acquisition of the norite and the first phase granophyre, respectively, Type 1 and Type 2, is probably the 1849 ± 3 Ma zircon age reported by Krogh *et al.* (1982). The tectonic rotations that occurred between the intrusion of the norite and the first granophyre phase appear to be restricted to the Basin. These rotations probably are best explained as the result of the collapse of a caldera on withdrawal of magma. Any paleomagnetically significant time gap between the intrusion of the norite and the first granophyre phase would be extremely unlikely.

A well-defined acquisition sequence exists between the Type 8, Type 6, Type 4, and Type 7 directions. The position of the Type 3 magnetization in this sequence is problematical. There are 2 possibilities, the Type 3 may either predate, or may immediately postdate the Type 8 magnetization. As discussed above, comparison of the Type 3 direction from the norite of the South Range with that of the remainder of the Complex, suggests this magnetization records a period of block fault rotation of the South Range. Yet, determinations of the Type 8 direction from the South Range do not show any systematic bias relative to similar vectors from the rest of the Basin. This lack of tectonic rotation implies that the Type 8 magnetization was later than the Type 3 direction. Conversely, it is possible that the rotation defined by the Type 3 direction is the result of inaccurate data resolution (*see discussion above*), in which case the Type 3 magnetization could postdate the Type 8 magnetization. Support for this option can be found in the relationship of the 2 vectors in the Foy Offset Dike in Hess Township. Type 3 is only found in sulphide magnetization, while the Type 8(?) is found in pyrrhotite, magnetite, and hematite. This appears to suggest that Type 8 predates Type 3.

The Type 3 magnetization is probably associated with the formation of localized intrusive bodies. Examples include sills that occur at the interface between the Onaping and Onwatin Formations of the White-water Group, and locally, in the upper parts of the South Range norite. In the previous section, it was argued that the Type 8 direction records the formation of a second phase granophyre. The acquisition sequence of the Type 3 and Type 8 magnetizations has important ramifications for the relative ages of the first and second phase granophyres. If Type 8 was acquired after Type 3, as suggested by the present data set, then the second phase granophyre must be much younger than first phase granophyre. At present, this is poorly controlled paleomagnetically. Even though the first and second phase granophyres have statistically identical mean remanence directions (Table 19.2), which superficially suggests that they acquired their remanence penecontemporaneously, when examined thoroughly,

this test does not provide a true discrimination of relative age. For example, we know that the Nipissing Diabase is at least 200 Ma older than either the granophyre first phase, or the granophyre second phase. Yet the Nipissing NIP-2 direction (Morris 1979; Roy and Lapointe 1976) is also not statistically distinct from either the first or the second phase granophyre mean remanence direction.

Presently available radiometric data are not much more helpful. In part this probably arises from the lack of significance given in earlier studies to the importance of different phases in the granophyre, and the possibility of multiple intrusion events in the Offset Dikes. Souch, Podolsky *et al.* (1969) reported a Rb-Sr age of 1717 ± 68 Ma for granophyre from the North Range and stated "although the norite and sublayer may be contemporaneous, both may be older than the granophyre". Rb-Sr data reported by Gibbins and McNutt (1975a, 1975b) from granophyre of the South Range gave an age of 1625 ± 130 Ma. Present paleomagnetic and radiometric data, then, tend to favour the option of the second phase granophyre being much younger than the first phase granophyre. Full resolution of this dichotomy, however, can only come from more radiometric dating of the identifiably different phases of granophyre and/or additional paleomagnetic studies of granophyre, especially from the southwestern corner of the Basin. It must be noted that if the younger age of Souch, Podolsky *et al.* (1969) is proven valid, then formation of the second phase granophyre would be temporally very similar to that given by Van Schmus (1971) for the Mongowin Pluton (1770 ± 75 Ma). Both these units have granophyric associations, and both are associated with the magmatic introduction of economically significant amounts of copper-nickel sulphides.

The Type 6 direction, whose acquisition post-dates the Type 8 direction, is also related to a separate phase of intrusion. A positive contact test from cross-cutting dikes in the Foy Offset Dike document this intrusive event. This direction is also commonly found in chemically distinct bodies in the Middle Zone, for example, near the Fraser Mine and on the Wisner traverse. Stevenson's (1963) "salt and pepper micropegmatite" is also characterized by the Type 6 direction. Interpretation of this unit as a separate intrusion differs from previous suggestions of Stevenson (1963) who considered it to be a chilled phase of the granophyre, and of Peredery and Naldrett (1975), who considered it to be a part of the recrystallized matrix of the basal breccia of the Onaping Formation. Nevertheless, there are no direct radiometric estimates for the age of this event.

The 2 youngest remanence directions in the Sudbury Igneous Complex (Tables 19.1 and 19.2) are the Type 4 and Type 7 directions. These are not associated with any documented intrusive events. Comparison of

the Type 7 direction, found in this study with Palmer *et al.*'s (1977) record of a Grenville Front Zone of remanence resetting in the Sudbury olivine diabase dikes, confirms that it is associated with thermal overprinting caused by heat flux related to the closely adjacent Grenville Orogeny. An acquisition age of around 950 Ma is preferred. In the absence of any direct evidence, association of the Type 4 direction with any particular geological event must be tentative. Gibbins and McNutt (1975b) recognized 2 regional radiometric resetting events, namely the Penokean (Hudsonian) Orogeny (1600 to 1800 Ma), and a cryptic (Elsonian) thermal event (1300 to 1450 Ma). Either one of these ages could be related to the Type 4 direction. If an age of around 1750 Ma is correct for the second phase granophyre, then the Elsonian age would be the preferred age for acquisition of the Type 4 direction.

Mineralization History of the Sudbury Igneous Complex

Only 3 (Type 3, Type 4, and Type 8) of the 7 remanence directions found in the Sudbury Igneous Complex are commonly associated with remanence residing in pyrrhotite.

From the discussions presented above, it is readily apparent that sulphide emplacement associated with the Type 8 and Type 3 remanence directions is probably related to the emplacement of their parent intrusive bodies. Occasionally, as in the Foy Offset Dike in Hess Township and in the Onaping Formation in Dowling Township, it is possible to detect 2 remanence types in closely adjacent outcrops. A direct implication of this situation is that one phase of mineralization must be epigenetic.

Many details of the Type 4 direction, where it is found in sulphide-rich bodies, confirm that this magnetization is the record of a broad-scale thermal event. First, Type 4 can be found within 60 m of low temperature phases carrying the Type 8 direction. Second, a plot of all Type 4 directions shows a broad "smear" indicating that remanence acquisition involved a definite period of time. Third, thermal demagnetization of Type 4 carrying specimens often give 2 unblocking temperatures for pyrrhotite; one for monoclinic and the other for hexagonal pyrrhotite (Morris 1982a). Fourth, the distribution of the sites carrying the Type 4 remanence direction has no correlation whatsoever with the distribution of any particular rock unit. This magnetization is found in all phases of the Sudbury Igneous Complex and in the overlying Onaping Formation of the Whitewater Group. As shown in Figure 19.4, the Type 4 magnetizations appear to outline a number of northwest-trending zones that cross-cut the Basin. In a regional context, these zones appear to have a spacing and trend that is very similar to the important Onaping Fault set (*see* Rousell, Chapter 5, this volume).

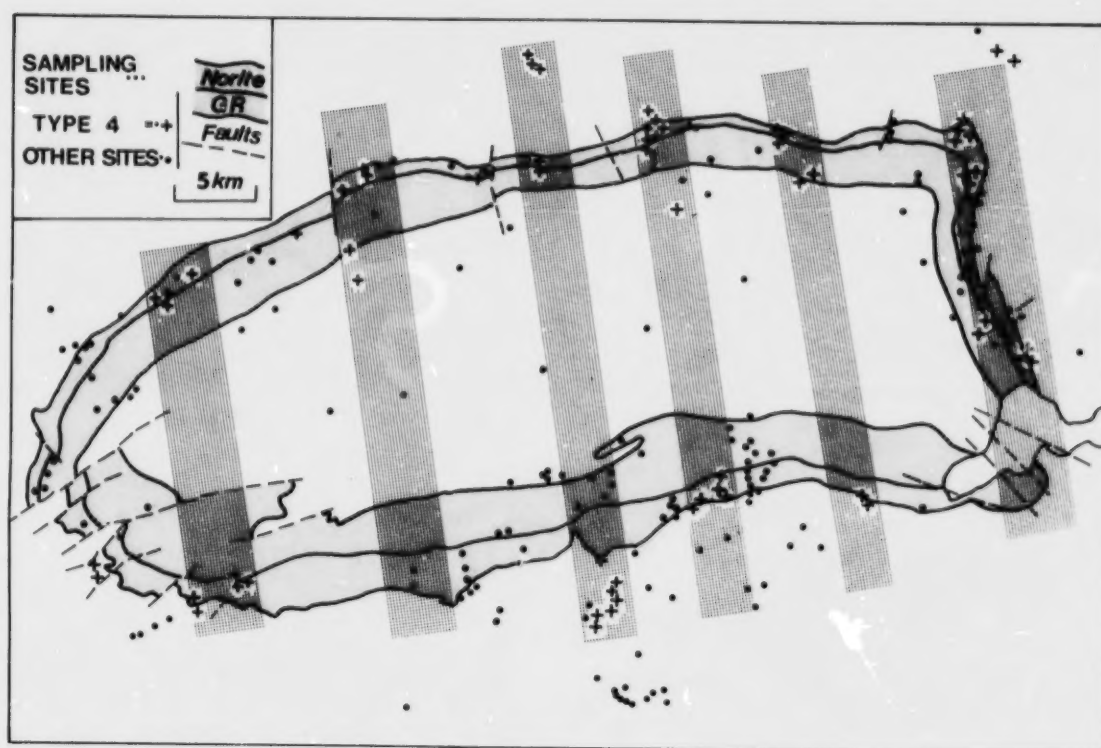


Figure 19.4. Distribution of sites carrying the Type 4 remanence direction, which appears to be intimately associated with significant sulphide concentrations.

Tectonic History of the Sudbury Region

Paleomagnetic *fold tests* on the Nipissing Diabase from the Cobalt Embayment and Elliot Lake areas have consistently been negative (Symons 1970, 1971; Symons and Londry 1975). There has been no significant regional deformation in the area north of the Murray Fault since the intrusion of the Nipissing Diabase. A positive *fold test* has been reported from Gowganda argillites of the Huronian Supergroup (Morris 1977). As the Nipissing Diabase presently occupies a series of domes and basins, the negative *fold tests* in the Nipissing Diabase of the Cobalt Embayment indicate that the Huronian Supergroup must have been subject to a regional deformation event prior to the intrusion of the Nipissing Diabase. This may be termed the F1 folding event.

Multi-component magnetization in Nipissing Diabase sills from the area between the Sudbury Igneous Complex and the Grenville Front, south of the Murray Fault, contain evidence of 2 positive fold tests (Morris 1981b). The first event involves deformation of the Nipissing Diabase that occurred soon after its intrusion (Figure 19.5). Some suggestion of syntectonic intrusion is provided by the agreement between the tilt-corrected directions from the outer faster-cool-

ing parts and the *in situ* directions from the inner slower-cooling parts of the sills. The paleomagnetic expression of this F2 folding event has presently only been reported for areas to the south of the Murray Fault. A clear record of a second phase of deformation in the Nipissing Diabase was provided by the thermal overprinting of this area by the norite. Correlation of the overprint directions measured from different limbs of folded Nipissing Diabase exposed south of the Murray Fault with the norite intrusion remanence direction, indicates that in this area, there has been a tightening of previously developed folds and a change in the dip direction of the axial planar surface (Figure 19.5). This F4 deformation is probably the same event that produced the tectonic rotation and buckling of the South and East Ranges as discussed above. If this correlation is valid, then this deformation must have occurred between the intrusion of the differentiate granophyre and the plagioclase-rich granophyre. This results from the observation that the second granophyre phase (the Type 8 remanence) does not show any large difference of remanence direction between the various limbs of the Basin.

Along the southeastern edge of the Sudbury Basin, the Huronian strata are vertical and face to the southeast. The overlying elements of the Sudbury Igneous Complex dip steeply and face to the northwest.

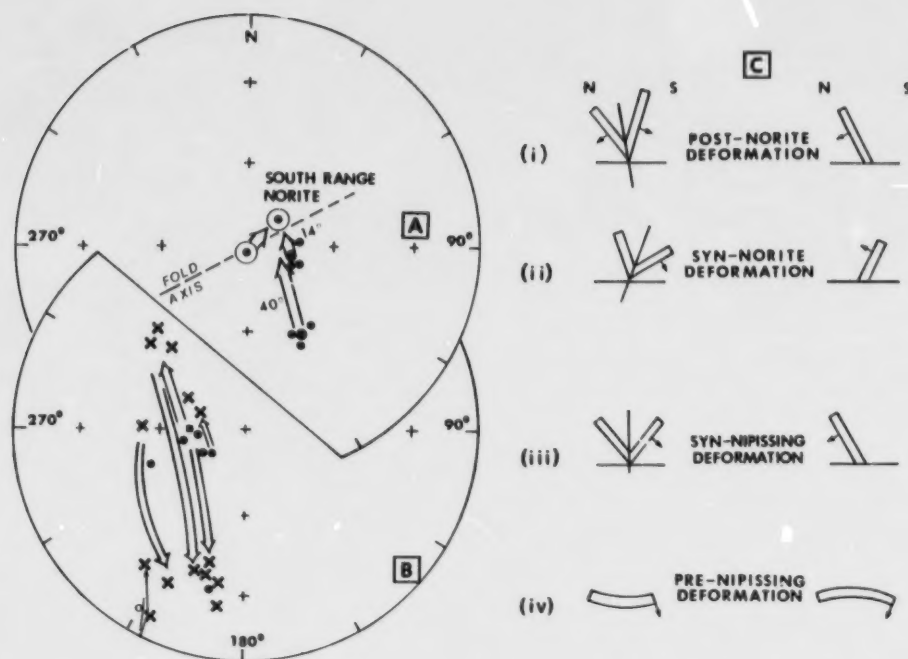


Figure 19.5. Summary of the evidence presented by Morris (1982) for multiple deformation of the Nipissing Diabase.

Figure 19.5a. Equal angle stereonet comparing the remanence directions from 2 limbs of a deformed Nipissing sill with the norite intrusion direction. This indicates differing amounts, but the same sense of rotation for each limb of the syncline.

Figure 19.5b. Equal angle stereonet showing the agreement between the directions from the 2 limbs of the syncline back to a subhorizontal position.

Figure 19.5c. Schematic of the tectonic history of the southern Southern Province as documented by the Nipissing Diabase:

1. Nipissing intruded into deformed Huronian sediments—the F1 event,
2. Nipissing deformed into steeply sided synclines—the F2 event,
3. Nipissing overturned prior to intrusion of norite—the F3 event, and
4. Folds in Nipissing tightened and norite deformed—the F4 event.

If the South Range norite was sub-horizontal at the time of intrusion, as shown in the previous section, then this demands that the Huronian strata of the South Range be overturned prior to the intrusion of the norite. To achieve the local overturning of the Huronian strata prior to the presence of some remanence directions in the Nipissing Diabase of the Sudbury region requires a F3, or Sudbury deformation event(?) that decreases in magnitude away from the Basin and that postdates the Nipissing Intrusion, but predates the intrusion of the norite.

Although the Grenville Province to the south appears to be recording a major deformational episode, it is quite clear that the effects of this orogeny for most of the Southern Province are restricted to the development of fault block rotations. There is no evidence in the Sudbury region of any significant penetrative

deformation associated with this orogeny. For example, paleomagnetic studies on the 1250 Ma Sudbury olivine diabase dikes do not reveal any regional fold pattern, as may be expected with any significant amount of Grenville deformation. Reports of different remanence directions associated with the Grenville Front tectonic zone, however, indicate the presence of differentially tilted blocks caused by the Grenville Orogeny (Palmer *et al.* 1977; Stupavsky and Symons 1983).

Metamorphic History of the Sudbury Region

Evidence of overprint magnetizations in the Huronian Supergroup (that is the Dollyberry volcanic rocks, the Thessalon volcanic rocks, and the Gowganda argil-

lites) indicate that the Supergroup was extensively metamorphosed at some time after the F1 folding event (Symons 1975; Roy and Lapointe 1976; Morris 1977; Symons and O'Leary 1978; Stupavsky and Symons 1983). The peak of this metamorphism may have either predated or postdated the intrusion of the Nipissing Diabase. If Morris' (1979) interpretation of the apparent NIP-2 direction in the Nipissing sill at Gowganda as a record of the metamorphic overprint direction is valid, then this metamorphic event must have postdated the intrusion of the Nipissing Diabase. This requires the metamorphic peak to be younger than 2150 Ma. Definition of a younger age limit for this regional metamorphic event is contentious. Card (1978) recognized the contact between the Huronian Supergroup and Sudbury Igneous Complex along the South Range as a metamorphic discontinuity having low to middle greenschist facies metamorphic assemblages north of the contact, and amphibolite grade metamorphism south of the contact. This implies intrusion of the Sudbury Igneous Complex after the peak of metamorphism. It follows that the metamorphism of the Huronian Supergroup and Sudbury Igneous Complex represent 2 temporally distinct events. In contrast, Fleet (1979) argued that parts of the South Range norite and the Copper Cliff Offset Dike have been subject to the same metamorphic event that affected the adjacent Huronian strata.

The limited paleomagnetic data presently available appear to favour Card's (1978) interpretation. First, no readily apparent trace of the regional metamorphic remanence signature found in the Huronian Supergroup has been detected in any part of the Sudbury Igneous Complex. Second, remanence overprints related to the intrusion of the norite have been documented in the Nipissing Diabase and the Copper Cliff rhyolite within 3 km of the contact. It is very unlikely that these magnetization overprints could have survived amphibolite grade metamorphism. Third, interpretation of the N2S and N2E directions as the result of metamorphism by intrusion of the first phase granophyre, presently revealed because of the higher degree of uplift of these areas, provides an internally consistent model that is compatible with local geological mapping.

Rb-Sr studies from the Huronian metasedimentary rocks indicate metamorphism occurred at about 1900 $\pm$ 50 Ma (Fairbairn *et al.* 1969). The best estimate of the age of formation of the norite is 1849 Ma. This essentially confirms the paleomagnetic view that the intrusion was penecontemporaneous with a period of metamorphism that selectively recrystallized isolated zones of the Southern Province.

Although most prominently defined in a zone immediately adjacent to the Grenville Front, remanence

overprinting related to the Grenville Event is only detected sporadically throughout the Sudbury Structure.

SUMMARY AND CONCLUSIONS

This chapter demonstrates that paleomagnetism can provide answers to some basic questions pertaining to the evolution of the Sudbury Structure. Perhaps the most crucial feature is the recognition that, rather than using the singular term "Sudbury Event" to describe the multiple magmatic, tectonic, and metamorphic pulses which have culminated in the Sudbury Structure, it is probably more correct to use the plural term "Sudbury Events."

Evidence presented in this article demonstrates that the Sudbury Structure contains the geological record of at least 4 (and possibly 5) temporally distinct magmatic pulses:

1. norite
2. granophyre (first phase)
3. (the Type 3 Onaping-Onwatin sills?)
4. the granophyre (second phase)
5. the Middle Zone quartz gabbro

During each of these intrusive pulses, magma was contemporaneously emplaced in the Main Mass, the Sublayer, and the Offset Dikes. Cross-cutting relationships can be commonly observed in many of the Offset Dikes. It can be confidently predicted that similar cross-cutting relationships will eventually be documented in the Main Mass. For example, the distinction of 2 granophyres should be made. If the Sublayer is accepted as being a composite of a number of intrusive pulses, then the previously contradictory evidence of contact relations between the Sublayer and the norite is explained.

Figure 19.6 summarizes the magmatic and tectonic evolution of the Sudbury Igneous Complex.

1. Initially, the norite was intruded into a shallow elongate basin that was gently plunging to the southwest.
2. After caldera collapse, the Sudbury Igneous Complex assumed the form of a symmetrical basin with uniform dips of around 40°. At this stage, the first phase granophyre was emplaced mainly in the zone above the norite.
3. This intrusion produced partial metamorphic resetting of magnetite in the underlying norite. This is more noticeable on the South Range where a deeper section of the intrusion is exposed.
4. The South and East Ranges were subsequently deformed relative to the remainder of the Basin.
5. The Onaping-Onwatin sills were emplaced(?).

EVOLUTION OF THE SUDBURY STRUCTURE

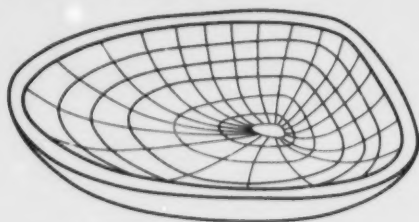
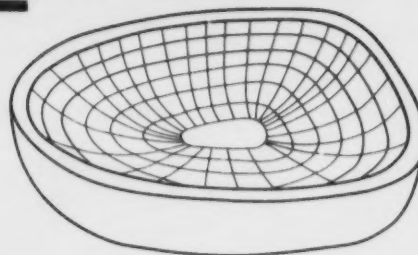
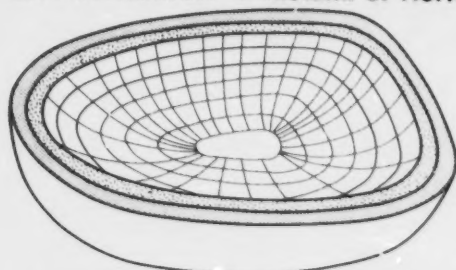
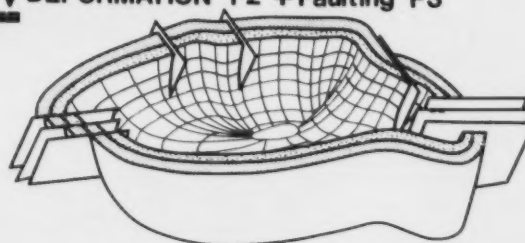
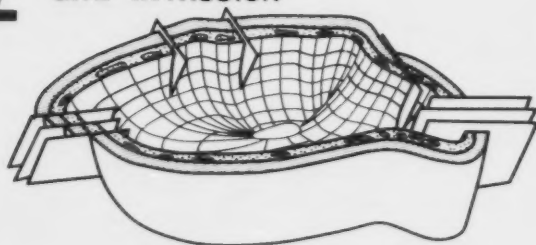
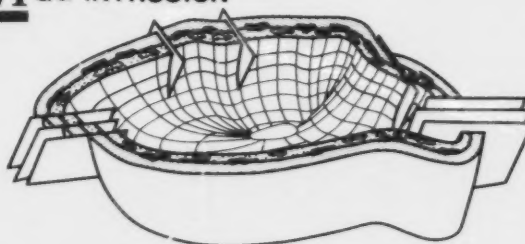
I NORITE INTRUSION**II** NORITE SLUMPING**III** GR1 INTRUSION + Metam. of Norite**IV** DEFORMATION F2 + Faulting F3**V** GR2 INTRUSION**VI** QG INTRUSION

Figure 19.6. Schematic of the tectonic and magmatic evolution of the Sudbury Structure:

1. norite intruded into an open syncline plunging gently to the southwest;
 2. norite slumping upon collapse of the covering domal structure;
 3. granophyre first phase intruded causing metamorphism of norite especially on the South and East Ranges;
 4. deformation, recorded by tectonic rotation of the South and East Ranges, followed by fault block rotation of the South Range;
 5. granophyre second phase intruded disrupting the granophyre first phase;
 6. Middle Zone quartz gabbro preferentially intruded along the boundary between the norite and the first phase granophyre.
6. The South Range suffered block fault rotation relative to the Basin.
 7. The second phase granophyre was intruded partly disrupting the first phase granophyre.
 8. The Middle Zone quartz diorite was intruded mainly along the contact between the norite and the first phase granophyre.

The absolute timing of these separate intrusive events is still somewhat speculative, in particular, the age of the second phase granophyre relative to the first phase granophyre.

Magnetizations residing in pyrrhotite are predominantly found with 3 characteristic remanence directions. Two phases of mineralization are related to specific intrusive events: namely, the Onaping-On-watin sills and the second phase granophyre. For the third and youngest phase of mineralization, which is

often found in the more massive sulphide deposits, no readily apparent intrusive body exists for which the mineralization can be associated. Rather, the available evidence favours association of this phase of sulphide emplacement with a regional epigenetic event.

Evidence from the Nipissing Diabase and its Huronian metasedimentary host rocks define 4 separate phases of deformation. These are:

1. the post-Huronian and pre-Nipissing (*circa* 2200 Ma) event
2. the post-Nipissing and pre-norite intrusion (*circa* 1900 Ma) event
3. the syn-norite intrusion (*circa* 1850 Ma) event (?)
4. the post-norite and pre-second phase granophyre event, which probably caused the differential buck-

ling and tilting of the South and East Ranges relative to the rest of the Basin after intrusion of the first phase granophyre

Regional events 2 and 3 appear to be restricted to an area south of, but including the Murray Fault Zone. The Grenville Orogeny produced little or no tectonic effect in the Southern Province.

In summary, paleomagnetic studies have shown the Sudbury region has a history of multiple intrusive pulses, multiple mineralization events, and multiple periods of deformation. These events occurred in the period 2200 to 1250 Ma. Initiation of intrusion of the Sudbury Igneous Complex followed close upon locally intense amphibolite grade metamorphism. Radiometric studies and regional geological mapping (Van Schmus 1976; James *et al.* 1961; Young 1982) have documented a very similar history for the Early and Middle Proterozoic of Michigan and Wisconsin. For example, Van Schmus (1980) reported a sequence of intrusive events associated with the Penokean Orogeny in Wisconsin that have many similarities to the geological history documented above for the Sudbury Region. Quoting Van Schmus (1980): "Two distinct pulses can be recognized. The older one began with mafic to felsic volcanism 1859 $\pm$ 20 Ma ago and was followed immediately by tonalitic to granitic plutonism 1840 to 1820 Ma ago. Structural studies indicate that these rocks were emplaced during the main phase of orogeny. The second pulse consisted predominantly of rhyolite and granophyric granite and occurred about 1760 $\pm$ 10 Ma ago." In Sudbury terminology, this could be directly equivalent to intrusion of the norite, 1849 $\pm$ 3 Ma ago followed soon after by the intrusion of the first granophyre phase; this intrusive phase closely approximates to the local peak of metamorphic activity. A second distinct pulse of granophyre was emplaced 1717 $\pm$ 68 Ma ago. Crucial tests of this comparison are more reliable age dates from the Sudbury region, and extensive paleomagnetic studies of the intrusive suites in Michigan and Wisconsin. No arguments have been presented for meteorite impact contributing to the geological evolution of either Michigan or Wisconsin. Is it not possible, therefore, to explain the major features of the Sudbury Basin by the same processes that occurred in Michigan and Wisconsin?

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GEOCHRONOLOGY

CHAPTER 20

Precise U-Pb Zircon and Baddeleyite Ages for the Sudbury Area

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ABSTRACT

New U-Pb ages on zircon (and baddeleyite) establish a consistent and relatively precise age-framework for the evolution of the Sudbury region.

Gabbroic rocks in the East Bull Lake and the Shakespeare-Dunlop Gabbro-Anorthosite Intrusions, believed to be cogenetic with the lowest volcanic rocks of the Huronian Supergroup, yield overlapping ages of $2480 \pm 10/-5$ Ma and 2491 ± 5 Ma, respectively. Syenite, areally associated with the East Bull Lake Gabbro-Anorthosite Intrusion, is dated at $2665 \pm 1.6/-1.4$ Ma, proving that the association of gabbro and syenite is fortuitous. The rhyolitic Copper Cliff Formation, which caps the lower volcanic part of the Huronian sequence, is slightly younger than the gabbro at $2450 \pm 25/-10$ Ma.

Zircons from the North Range felsic norite, the North Range mafic norite, and the South Range black norite of the Sudbury Igneous Complex yield overlapping ages of $1848.9 \pm 4.0/-2.7$ Ma, $1850.0 \pm 3.4/-2.4$ Ma, and 1850.0 ± 1.3 Ma corroborating earlier U-Pb dates. An age of 1850 ± 1 Ma, obtained by averaging the 3 dates, is proposed for the intrusion of the norite. Baddeleyite from a granophyre indicates an age of 1850.5 ± 3 Ma showing that norite and granophyre are essentially coeval.

Zircons in samples from both the Levack Gneiss and the Onaping Formation are characterized by extensive cracking along crystallographically oriented planes, a unique feature believed to be the result of shock metamorphism. Concordant zircon of a pegmatoid in the Levack Gneiss Complex indicates late Archean metamorphism at 2647 ± 2 Ma. Zircon analyses from 4 Levack Gneiss Complex and 3 Onaping Formation samples define a discordia line with an upper intercept age of 2711 ± 7 Ma and a lower intercept age of 1836 ± 14 Ma. We interpret the upper age as being the primary crystallization age, while the lower age is due to resetting by shock metamorphism. Newly

grown 1850 Ma old zircons occur in a Levack Gneiss Complex sample adjacent to the norite contact. No such zircons were found in glasses of the Onaping Formation.

An age of $2388 \pm 20/-13$ Ma dates the intrusion of the granitic Murray Pluton into Huronian sedimentary rocks. Zircons in a granitic dike cutting the norite yield a scattered data pattern reflecting the presence of inherited components and complex post-crystallization Pb loss. Nevertheless, the position of the data points in relation to the norite data suggest that the dike was emplaced shortly after cooling of the norite.

INTRODUCTION

Highly consistent U-Pb ages allow a re-evaluation of previous whole rock Rb-Sr and mineral ages for most of the important units in the Sudbury area. Although the early comprehensive Rb-Sr investigations of Fairbairn and Hurley (Fairbairn *et al.* 1960, 1965, 1969) marked a major advance at the time, most of the early results now serve as examples of how complex poly-phase mineral aggregates (whole rocks) have responded to a variety of geological events in different ways depending on their mineral content and stability, whole rock permeability, and deformation state. For example, the Gowganda Formation gave an isochron of 2240 ± 87 Ma when sampled at low metamorphic grade, but gave 1772 ± 105 Ma ($\lambda = 1.42 \times 10^{-11} \text{ a}^{-1}$) when sampled at higher metamorphic grade in the Espanola-Sudbury area (Fairbairn *et al.* 1960, 1965, 1969). Clearly, isotopic exchange accompanied regional metamorphism, but aside from this the reliability of an isochron obtained on a detrital sediment needs to be questioned, both because in this case the detritus comes from an Archean basement, and because diagenesis may also cause isotopic exchange. Similar factors can explain the scatter and inaccuracy of other sediment isochrons for other units in the region.

As will be noted later, the Rb-Sr whole rock ages for the Sudbury Igneous Complex also vary with rock type. An isochron based mainly on granophyre samples gave an age of 1668 ± 19 Ma ($\lambda = 1.42 \times 10^{-11} \text{ a}^{-1}$); (Fairbairn *et al.* 1968), whereas an isochron age of 1915 ± 98 Ma was reported by Gibbins and McNutt (1975a) for the norite, a surprising difference considering that both rocks experienced the same regional geological conditions. An age of 1843 ± 133 Ma reported by Hurst and Farhat (1977) for the norite agrees within the large quoted error and brings out the difficulty of obtaining precise ages by the Rb-Sr method on rocks with low Rb-Sr ratios. Very high precision in measuring present day strontium isotopic compositions is required. Even if this is accomplished using state of the art instrumentation, the requirement that initial ratios must be constant and that samples must remain closed systems, must be met in consideration of the small radiogenic increments between the samples. As a further example of the difficulties in obtaining closed system Rb-Sr whole rock behaviour under the same regional conditions, we should note the 1400 ± 65 and 1449 ± 55 Ma ($\lambda = 1.42$) reported for the Onaping Formation clasts by Fullager *et al.* (1971), for samples from a region where biotite Rb-Sr and K-Ar ages of about 1600 Ma have been reported (Gibbins and McNutt 1975b). Perhaps the Onaping Formation glasses did not devitrify until the age indicated by these isochrons, but the norite biotites were not affected. In general, the consistent U-Pb results presented here will indicate that most whole rock Rb-Sr systems in the area have been disturbed.

Perhaps the most fundamental result from the early work is the different cooling histories noted for the North and South Ranges. As summarized by Gibbins and McNutt (1975b), biotites from the North Range norite give ages of about 1600 Ma, whereas those in the South Range average 1290 Ma; clearly, the South Range was uplifted and cooled long after the North Range.

In contrast to the Rb-Sr method that has produced complex age results, the new data by the U-Pb zircon method are very self-consistent. As noted in a more extensive discussion of the 2 methods as applied to the norite of the Sudbury Igneous Complex in Krogh *et al.* (1982), the U-Pb technique is unique in having 2 parent-daughter pairs (Faure 1977). The measured data determine if an open system has been analyzed and give an indication of how much lead loss (or uranium gain) has occurred. Utilizing this feature, we have refined the method by identifying, or creating and isolating, in a given zircon population, those grains or parts of grains that have undergone little or no lead loss since the time of their formation.

For example, in each study presented here, samples weighing in excess of 40 kg were collected and the

zircons concentrated. From these, the least paramagnetic fraction is isolated, and crack-free grains are selected. To obtain samples with a minimum of lead loss, all geological surfaces are removed by abrasion (Krogh 1982a) and in most cases weakly paramagnetic grains are removed using a simple high gradient paramagnetic selection device, the tip of a sharp soft iron wire on a bar magnet (Krogh 1982b). If all grains are paramagnetic as is the case for several rocks studied here, the clearest grains in the least paramagnetic fraction are selected and abraded, and when clear grains are extremely scarce, the sample size is reduced to 10 to 30 micrograms of the highest quality material. In such cases, we make a precise analysis on as little as 1 to 5 nanograms of lead (10^{-9} g) and maintain a high sample to background ratio because of our low contamination procedures; lead blanks of 10 to 20 picograms (10^{-12} g) are routinely attained using methods described in Krogh (1973). The ages and error estimates along with the probability that data fit a line within our estimated analytical uncertainty, were estimated according to Davis (1982).

In his introduction to the Geological Association of Canada special paper New Developments in Sudbury Geology, Guy-Bray (1972) noted that "At Sudbury a most pressing need is for additional high-quality radiometric age determinations to provide a more secure framework for observed events." At the same time he noted that "so far Sudbury has proved to be a type area for demonstrating the difficulties of obtaining meaningful ages for rocks affected by multiple igneous and metamorphic events." We now hope to fulfill some of this need with our new U-Pb studies reported here and in progress. At the same time, we would like to note that the detailed early work has been a useful source of information and inspiration to our group.

NEW U-Pb ZIRCON AGES FOR THE HURONIAN SUPERGROUP

The depositional age for the Huronian Supergroup has proven difficult to determine due to the lack of materials amenable to precise isotopic dating. An early significant minimum age of 2110 ± 80 Ma for the cross-cutting Nipissing Diabase was first measured by Van Schmus (1965) and later confirmed by Fairbairn *et al.* (1969), who measured an age of 2116 ± 27 Ma ($\lambda = 1.42 \times 10^{-11} \text{ a}^{-1}$). More recently a minimum age of $2333 \pm 32/-22$ Ma was reported by Frarey *et al.* (1982), who analyzed zircons from the granitic Creighton Pluton which cuts lower Huronian Supergroup rocks near Sudbury. A maximum age for the Huronian Supergroup of 2555 Ma is often quoted, based on 2 biotite ages for basement granites as reported by Van Schmus (1965). This maximum age, however, is invalid and should not be used because the

youngest granites in the region have U-Pb zircon ages of 2668 Ma (Krogh and Turek 1982).

Precise dating of the Huronian Supergroup has also proven difficult in the current investigation. Numerous samples from the mildly alkalic volcanic rocks (Thessalon Formation), which occur near the base of the Huronian Supergroup, failed to yield zircons for dating. Instead, zircons were obtained from gabbros and related granophyres that are associated with the mafic flows of the lower Huronian Supergroup, but those proved to be very rich in uranium and susceptible to open system behaviour. The rhyolitic Copper Cliff Formation, which was also studied, presented a similar challenge with high uranium zircons.

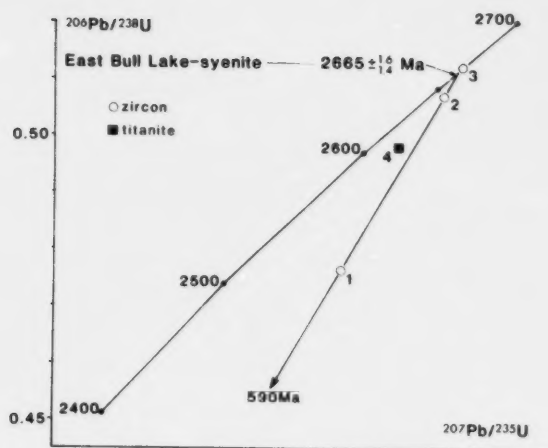


Figure 20.1. Concordia diagram with zircon and titanite data for the East Bull Lake syenite. Numbers refer to those in Table 20.1.

The East Bull Lake and the Shakespeare-Dunlop Gabbro-Anorthosite Intrusions

The East Bull Lake Gabbro-Anorthosite Intrusion, situated about 90 km west of Sudbury, is one of several layered gabbro-anorthosite intrusions that are areally associated with lower Huronian Supergroup supracrustal rocks. These rocks tend to straddle the northern boundary between the Huronian Supergroup and the Superior Province basement. Although the exact relationship to the Huronian rocks is not certain, it is generally believed that the lower Huronian mafic volcanic rocks and the gabbros are cogenetic (Card *et al.* 1977).

The East Bull Lake Gabbro-Anorthosite Intrusion is generally considered to consist of a northern

mafic layered unit, and an areally equivalent southern unit of weakly layered syenite (James *et al.* 1983). The 2 units are separated by faults or diabase dikes so that their field relationships are uncertain.

Samples for isotopic dating were collected from a metre scale layered olivine norite zone in the East Bull Lake body, and from the coarse-grained variety of syenite described by James *et al.* (1983).

A second similar intrusion, the Shakespeare-Dunlop Gabbro-Anorthosite Intrusion, which occurs about 66 km southwest of Sudbury at Agnew Lake, has been described by Card and Palonen (1976) and James and Harris (1977). In this case, a granophyre occurring at the uppermost stratigraphic level was sampled for isotopic dating. The sample is massive, medium grained, and contains graphically intergrown quartz and feldspar with aggregates of biotite and epidote.

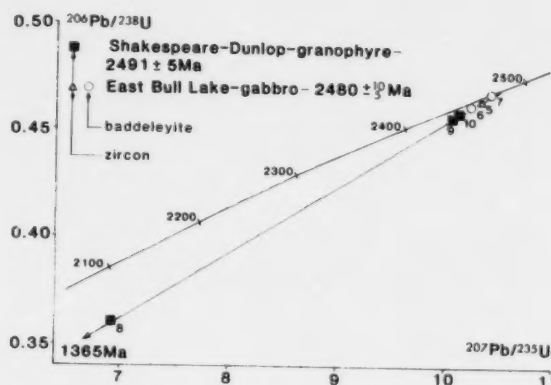


Figure 20.2. Concordia diagram with zircon and baddeleyite data for the Shakespeare-Dunlop granophyre and the East Bull Lake Gabbro.

Isotopic Results

An age of 2665 ± 1.6 – 1.4 Ma (with a 15% probability of fit) for the syenite at East Bull Lake based on 2 abraded and 1 unabraded zircon fractions (Analyses 1 to 3, Table 20.1, Figure 20.1), is inconsistent with all other data for Huronian rocks. We conclude, therefore, that the syenite is Archean and that its position beside the gabbro is fortuitous. A single analyzed titanite (Analysis 4, Table 20.1, Figure 20.1) separate has a minimum age of 2641 Ma, as if slightly disturbed during a post crystallization thermal event.

The East Bull Lake Gabbro-Anorthosite Intrusion yields a U-Pb isotopic age of 2480 ± 10 – 5 Ma based on the analysis of 2 fractions of baddeleyite (Analyses 6 and 7, Table 20.1, Figure 20.2) and 1 zircon fraction (Analysis 5, Table 20.1, Figure 20.2). The 3 data points fit a line with 20% probability of fit within experimental error. In this case, more than 50 kg of olivine gabbro provided only a few milligrams of zircon

and after selection and abrasion, a sample weighing 0.1 mg was analyzed. A similar small sample of abraded baddeleyite was also analyzed to give a point which is only 0.5% discordant.

An age of 2491 ± 5 Ma for the Shakespeare-Dunlop Gabbro-Anorthosite Intrusion was derived from 3 analyzed zircon fractions that are colinear, with a 52% probability of fit (Analyses 8, 9, and 10, Table 20.1, Figure 20.2). The zircons in this rock are all relatively rich in uranium, chemically altered, and relatively discordant. The best fraction consisted of only 0.035 mg of the least-cracked, least-paramagnetic, abraded zircons, but is still 6% discordant. In this case, a lower intercept of 1365 Ma was obtained, perhaps indicating a mild thermal event at this time as reflected in the 1300 Ma biotite age for the granitic Cutler Pluton to the south (Fairbairn *et al.* 1960).

The Copper Cliff Formation

In the Sudbury area, the lower part of the Huronian Supergroup consists predominantly of thick tholeiitic basalt flows and minor sedimentary rocks which are overlain by the rhyolitic Copper Cliff Formation. Zircons from this rhyolite are relatively high in uranium, highly cracked and turbid, and tend to be highly discordant. In this case, we were forced to analyze extremely small samples of the best possible material. Analyses 13, 14, and 15 in Table 20.1 and Figure 20.3 represent 76, 7, and 14 micrograms of zircon, respectively. For these analyses of crack-free grains, the normal trend of increased discordance with increased uranium is observed. Analyses of cracked grains,

however, yield anomalous discordance because they have lower uranium contents, but are more discordant. Abraded, cracked grains represented by Analysis 12 plot close to a reference line projected to 1850, the age of the Sudbury Event. Analysis 11 plots below the reference line as expected, since it was not abraded and probably suffered recent surface-related lead loss.

The relatively high degree of discordance for low uranium, cracked grains implies that the discordance may have been induced by the cracking during the Sudbury shock event as will be described later for zircons from the Onaping Formation and the Levack Gneiss Complex. In any case, the 1850 Ma lower intercept can be combined with data for the most concordant point to yield a maximum age estimate of 2475 Ma for the Copper Cliff Formation. An alternative interpretation is based on the concept that the crack-free grains were not affected by the Sudbury Event, and that the top 3 data points project to $2444 \pm 8/-4$ Ma with a 46% probability of fit and a lower intercept of 674 Ma. Taken together, we propose an age of $2450 \pm 25/-10$ Ma as the best age estimate for the Copper Cliff Formation. This age is compatible with an emplacement age for the underlying basic volcanic rocks of $2480 \pm 10/-9$ or 2491 ± 5 Ma as measured on gabbro and granophyre, respectively, believed to be coeval with the volcanism.

THE AGE OF THE SUDBURY NORITE AND GRANOPHYRE

Introduction

Early attempts to date the Sudbury Igneous Complex by the Rb-Sr whole rock method resulted in ages ranging from about 1668 ± 19 Ma to 1915 ± 98 Ma for the granophyre (Fairbairn *et al.* 1968) and norite proper (Gibbins and McNutt 1975a). Hurst and Farhat (1977) reported an age of 1843 ± 133 Ma by the same method ($\lambda = 1.42 \times 10^{-11} \text{ a}^{-1}$). The relatively large errors and range of measured values result from the low Rb-Sr ratios of the norite and the resulting small increments of radiogenic strontium present, as well as variable susceptibilities of different rock types to post crystallization migration of the dating elements.

In contrast to the whole rock system where radiogenic additions are small and where the rocks contain minerals formed or reformed at various times, the analyzed zircons from the norite are highly radiogenic, and formed only during a single magmatic crystallization event. These grains can be selected and abraded (Krogh 1982a, 1982b) to create and isolate parts of grains that have suffered little or no lead loss over their entire history. U-Pb zircon ages from different norite samples are highly consistent.

Successful dating of norite began when we first

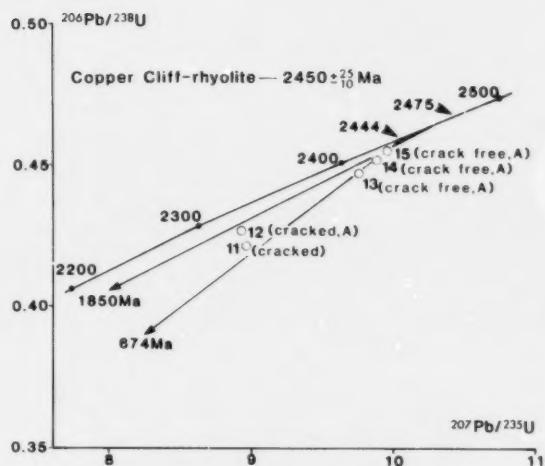


Figure 20.3. Concordia diagram with zircon data for the Copper Cliff Formation; 2444 Ma is the upper intercept of the discordia line through data points 13 to 15, whereas 2475 Ma is the upper intercept of a discordia line through 1850 Ma and Analysis 15, Table 20.1, $2450 \pm 25/-10$ Ma is the estimated age of the rhyolite.

TABLE 20.1: U-Pb DATA OF SAMPLES FROM THE HURONIAN SUPERGROUP.

SAMPLE	WEIGHT (mg)	U (ppm)	MEASURED ¹ ²⁰⁶ Pb/ ²⁰⁴ Pb	COMMON					
				Pb (ng) ²	²⁰⁷ Pb/ ²⁰⁶ Pb ³	²⁰⁸ Pb/ ²⁰⁶ Pb ³	²⁰⁶ Pb/ ²³⁸ U ⁴	²⁰⁷ Pb/ ²³⁵ U ⁴	²⁰⁷ Pb/ ²⁰⁶ Pb ⁴ age (Ma)
East Bull Lake-syenite (N-79-2)									
1) Z, MO, br-tr	0.938	451	4864	2.45	0.18134	0.3043	0.4763	11.769	2645.6
2) Z, NMO, cl, A	0.314	276	18203	0.073	0.18134	0.2419	0.5070	12.662	2663.1
3) Z, NMO, cl, A	0.099	217	6802	0.021	0.18127	0.2749	0.5124	12.803	2664.0
4) S, M10 (1.0A), br-tr	0.870	173	469.6	9.81	0.20453	1.367	0.4978	12.265	2641.0
East Bull Lake-gabbro (N-79-1)									
5) Z, NM10, A, cl	0.108	403	11975	0.026	0.16179	0.3904	0.4625	10.312	2473.4
6) b, M3, br-op	0.796	671	61541	0.144	0.16146	0.0078	0.4609	10.253	2470.0
7) b, M3, A, br-op	0.083	1197	29699	0.031	0.16200	0.0148	0.4665	10.416	2476.0
Shakespeare-Dunlop-granophyre (C-81-16)									
8) Z, M2, A, op-lu	0.017	1741	2220	0.227	0.14377	0.2245	0.3600	6.937	2224.0
9) Z, M3, A, cl-lu	0.274	1428	18730	0.490	0.16082	0.2432	0.4555	10.084	2461.3
10) Z, M2, A, cl-lu	0.035	1070	6016	0.072	0.16144	0.1122	0.4563	10.122	2464.7
Copper Cliff-rhyolite (C-81-19)									
11) Z, NMO, lu, cr	0.086	522	2842	0.321	0.15737	0.1894	0.4222	8.964	2390.6
12) Z, NMO, A, lu, cr	0.016	648	2005	0.060	0.15364	0.1638	0.4264	8.913	2364.0
13) Z, MO, A, cl-br, lu	0.076	1624	5675	0.500	0.15982	0.1293	0.4479	9.756	2434.0
14) Z, NMO, A, cl, lu	0.007	1255	2112	0.049	0.16056	0.1441	0.4524	9.880	2438.5
15) Z, NMO, A, cl, lu	0.014	784	3765	0.030	0.15899	0.1398	0.4552	9.945	2439.1

Notes:

1) corrected for fractionation

2) corrected for common Pb in spike

3) corrected for fractionation, spike, and blank

4) corrected for fractionation, spike, blank, and initial common Pb

Z = zircon, S = titanite; b = baddeleyite; M, NM = magnetic, non magnetic on Frantz isodynamic separator at 1.7 Amp. (unless otherwise indicated) and at indicated angle of tilt; br = brown; tr = translucent; cl = clear, colourless-pink, transparent; A = abraded; op = opaque; tu = turbid; ltu = least turbid

learned from geologists of Inco Limited (for example, D. Phipps, Staff Geologist, Inco Limited, personal communication, 1972) that zircons were present in several norites they had studied. The zircons occur both as discrete unzoned grains and as skeletal crystals which can be found in granophytic patches between plagioclase laths (Krogh *et al.* 1982). Both the lack of zoning and the skeletal structures suggest late crystallization, as does their relatively high uranium content. No trace of cores were found in any of 3 norite and 3 granophyre samples studied. Chemical alteration is fairly common in the norite zircons when viewed in reflected light after an HF vapour etch (Krogh and Davis 1974). The alteration is invisible under a binocular microscope in incipient stages, but becomes visible as white patches within clear, straw yellow to brown grains as it progresses. In general, the norite zircons, with altered grains removed, are relatively concordant when compared with other samples having similar high uranium levels.

The initial dating study of norite zircons began at the Carnegie Institution of Washington in a collaborative project with R.H. McNutt of McMaster University. Two ages based on the early analyses and a limited number of new analyses are 1849.6 ± 3.4/-3.0 Ma and 1849.4 ± 1.9/-1.8 Ma for the North and South Range

norites, respectively (Krogh *et al.* 1982). A second study was initiated at the Royal Ontario Museum as an interlaboratory calibration, using different isotopic tracers and mass spectrometers. Because we had already selected and removed the large, clear, crack-free grains during the early study, the second investigation was only possible because of the development of new techniques to create and isolate relatively concordant material from inferior starting material (Krogh 1982a, 1982b). Thus, by utilizing our small-sample capability, we were able in the second study to obtain new data that were, in general, more concordant than had been obtained at Carnegie. To make the comparison more meaningful, old and new data were all adjusted to National Bureau of Standards isotopic standards.

Taken together, the results from the 2 laboratories, using samples from 2 localities, must make the Sudbury Igneous Complex one of the most precisely dated igneous bodies in the world.

The North Range Felsic Norite

Zircons from the felsic norite (location shown in Figure 20.4) (Analyses 1 to 5, Table 20.2, Figure 20.5) were abraded to remove surface correlated lead loss and selected to avoid trace amounts of chemical alter-

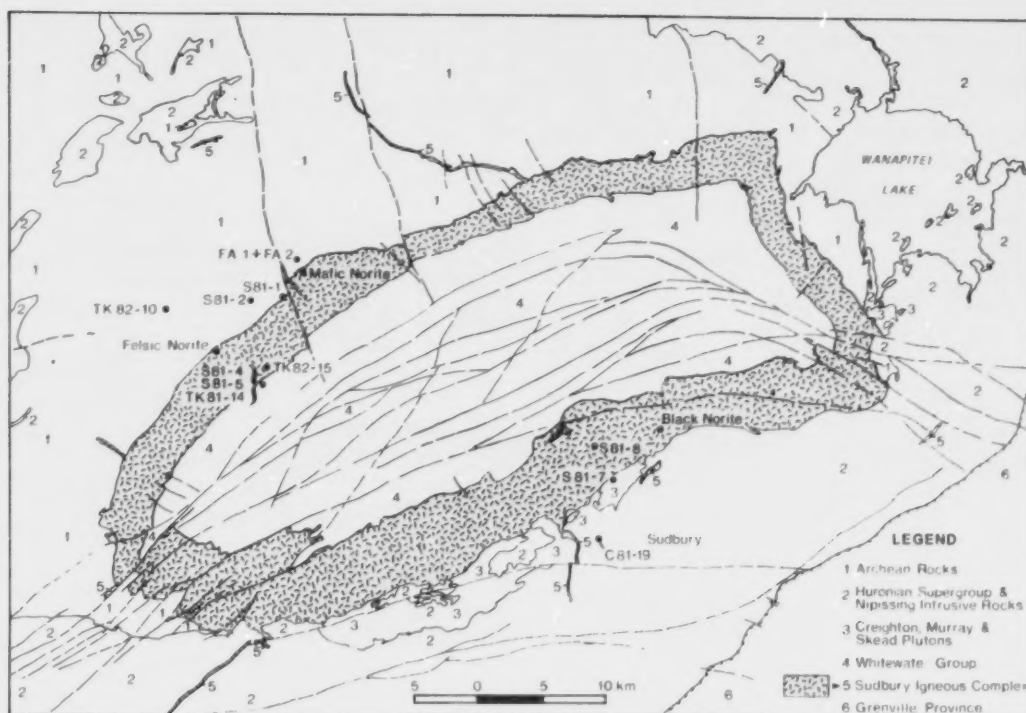


Figure 20.4. Geological map of the Sudbury area showing sample locations.

TABLE 20.2: U-Pb DATA OF SUDBURY NORITE AND GRANOPHYRE.

SAMPLE	WEIGHT (mg)	U (ppm)	MEASURED ¹ ²⁰⁶ Pb/ ²⁰⁴ Pb	COMMON					²⁰⁷ Pb/ ²⁰⁶ Pb ⁴ age (Ma)
				Pb (ng) ²	²⁰⁷ Pb/ ²⁰⁶ Pb ³	²⁰⁸ Pb/ ²⁰⁶ Pb ³	²⁰⁶ Pb/ ²³⁸ U ⁴	²⁰⁷ Pb/ ²³⁵ U ⁴	
North Range Felsic Norite									
1) MO, cl, A	0.022	1291	4188	0.13	0.11450	0.1121	0.3287	5.116	1846.4
2) + 200, NO, A, ↓	0.740	1306	26937	0.70	0.11332	0.3908	0.3260	5.073	1846.0
3) + 200, NO, A	0.090	1254	8073	0.28	0.11402	0.4167	0.3246	5.046	1844.2
4) + 100, NO, A	0.570	1474	4203	3.86	0.11577	0.4180	0.3203	4.974	1842.0
5) + 200, NO	0.350	1706	8324	1.38	0.11416	0.3952	0.3191	4.954	1842.0
South Range Black Norite									
6) + 200, MO, A	0.120	1470	16590	0.21	0.11366	0.6350	0.3302	5.150	1850.0
7) + 200, NO, sk	0.500	317	5502	0.57	0.11516	0.3771	0.3276	5.104	1848.1
8) + 100, NO	0.960	848	6349	2.47	0.11475	0.5163	0.3200	4.971	1843.0
9) 100-200, M7	1.170	1147	2533	9.27	0.11705	0.5636	0.2893	4.458	1828.2
10) 100-200, M3	0.610	2014	3356	6.24	0.11555	0.1156	0.2822	4.341	1825.0
11) 100-200, M5	1.140	1671	1678	18.01	0.11872	0.6291	0.2617	3.994	1811.0
North Range Mafic Norite									
12) + 200, M1, A	0.070	720	3809	0.27	0.11569	0.7377	0.3300	5.144	1849.0
13) + 200, N1	0.200	1143	1902	2.34	0.11963	0.6865	0.3206	4.984	1844.0
North Range Granophyre (TK-82-15)									
14) baddeleyite	0.054	2027	26950	0.039 ²	0.11308	0.014	0.3269	5.097	1849.3

Notes:

1) corrected for fractionation

2) corrected for common Pb in spike

3) corrected for fractionation, spike, and blank

4) corrected for fractionation, spike, blank, and initial common Pb

M, NM = magnetic, non magnetic on Frantz isodynamic separator at 1.7 Amp. and at indicated angle of tilt; + 200 = size in mesh;

A = abraded; † = non magnetic on high-gradient magnetic pin; sk = skeletal

ation. In some cases, final selection was made under high index oil or in polarized light under a petrographic microscope, where incipient chemical alteration, associated with discordance, is more visible. An age of $1848.9 \pm 4.0/-2.7$ Ma with an 85% probability of fit within experimental error is calculated from the 5 analyses. Results from the more concordant Carnegie results shown for comparison on Figure 20.5, were not used in the regression.

The North Range Mafic Norite

Two fractions of zircon from a mafic norite horizon that occurs beneath the felsic norite in the North Range were selected and analyzed (Analyses 12, 13, Table 20.2, Figure 20.6). As usual, the abraded, crack-free grains are almost concordant within experimental error.

The 2 analyses define an age of $1850.0 \pm 3.4/-2.4$ Ma, which agrees within error with the age of the associated felsic norite.

The North Range Granophyre

A single analysis of baddeleyite (ZrO_2) (Analysis 14, Table 20.2, Figure 20.5) from the plagioclase-rich granophyre that underlies the Onaping Formation on Highway 144 (Figure 20.4) in the North Range, provides a relatively precise age estimate, because we need only to correct for 2% lead loss and the analysis itself has an error of ± 2 Ma. This correction can be done assuming that the loss occurred 260 Ma ago to give an age of 1852 Ma, or we can assume that the extremely fine grain size had produced a surface correlated recent loss in which case an age of 1849 Ma would be obtained. Since each alternative is equally probable, we chose to combine the results to estimate an age of 1850.5 ± 3.0 Ma for the North Range granophyre.

It is interesting to note that baddeleyite is relatively concordant when compared with zircon, even though the baddeleyite, in this case, contains about 2000 ppm uranium. This may indicate that radiation damage was not accumulated in the baddeleyite so that chemical alteration and lead loss are not promoted.

In conclusion, it is highly probable that the norite and granophyre formed at the same time about 1850 ± 3 Ma ago.

The South Range Black Norite

Six analyzed zircon fractions from the black norite located on Figure 20.4, variously selected and abraded to avoid chemical alteration, yield an age of 1850.0 ± 1.3 Ma (Analyses 6 to 11, Table 20.2) with a 59% probability of fit. The top 3 analytical points are shown in Figure 20.6 along with data previously obtained at the Carnegie Institution of Washington, which again were not included in the age estimate.

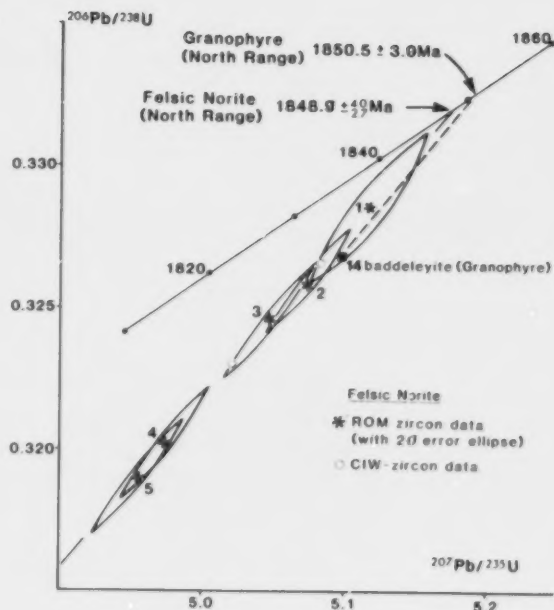


Figure 20.5. Concordia diagram with zircon data for the North Range felsic norite and 1 baddeleyite analysis of the North Range granophyre. The $1848.9 \pm 4.0/-2.7$ Ma age of the felsic norite is calculated from the 5 ROM (Royal Ontario Museum) data points and does not include the 3 CIW (Carnegie Institution of Washington) data points. The 1850.5 ± 3.0 Ma age of the granophyre is estimated from the almost concordant baddeleyite analysis.

Summary of Results for the Sudbury Norite and Granophyre

In Table 20.3, the authors present the age data for the 4 units discussed above, along with data for the 2 norite samples previously studied at the Carnegie Institution of Washington, and give statistical parameters for various combinations of data. All the combinations of data are relatively colinear, although as noted earlier, certain highly discordant altered zircons in the felsic norite have been omitted. The new ages for the North Range felsic norite and mafic norite, and South Range black norite, respectively, of $1848.9 \pm 4.0/-2.7$, $1850.0 \pm 3.4/-2.4$, and 1850.0 ± 1.3 Ma are essentially identical and suggest our errors may be overestimated. Even the previous determination of $1849.4 \pm 1.9/-1.8$ Ma for the black norite, using the same samples but different isotopic tracers and mass spectrometers, at the Carnegie Institution of Washington, agrees well within error with the new values. Comparisons with the previously determined felsic norite age are not advised because we now know that the discordant points are not colinear even though the age appears valid. Because the data are coincident, all 12 analyses of zircons from the black norite can be combined to give an age of 1849.7 ± 1.1 Ma, using data

TABLE 20.3: SUMMARY OF AGE DATA OF SUDBURY NORITE AND GRANOPHYRE.

ROCK UNIT (NR = NORTH RANGE) (SR = SOUTH RANGE)	NO. OF ANALYSES	UPPER (LOWER) INTERCEPT AGE (in Ma)	PROBABILITY OF FIT
NR-Felsic Norite			
ROM-data	5	1848.9 $\pm$ 4.6/-2.7 (321)	85%
CIW-data	4	1849.6 $\pm$ 3.4/-3.0 (484)	51%
NR-Mafic Norite	2	1850.0 $\pm$ 3.4/-2.4 (296)	-
NR-Granophyre	1	1850.5 $\pm$ 3.0	-
SR-Black Norite			
ROM-data	6	1850.0 $\pm$ 1.3 (265)	59%
CIW-data	6	1849.4 $\pm$ 1.9/-1.8 (260)	57%
ROM + CIW data	12	1849.7 $\pm$ 1.1 (263)	63%
SR-Black Norite + NR-Mafic Norite + NR-Felsic Norite		weighted average of 3 individual age determinations (ROM data) 1849.9 $\pm$ 1.1	

from the 2 laboratories. Alternatively, the 3 age determinations from the black norite, mafic norite, and felsic norite measured at the Royal Ontario Museum laboratory can be averaged to yield an age of 1849.9 ± 1.1 Ma.

Our best age then, for the norite component of the Sudbury Igneous Complex can be rounded off and quoted as 1850 ± 1 Ma. The Sudbury granophyre very likely formed at the same time because our best age estimate using limited data is 1850.5 ± 3 Ma.

ISOTOPICALLY AND PHYSICALLY SIMILAR (SHOCKED) ZIRCONS IN THE LEVACK GNEISS COMPLEX AND ONAPING FORMATION

Zircons in the Levack Gneiss Complex, which lies north of the Sudbury Igneous Complex, are unique in so far as they contain abundant crystallographically oriented planar features which to our knowledge have never been previously described. Under a binocular microscope, the abundance of such planar features varies from grain to grain. Where these planar features are extensive, grains develop a chalky, white appearance. At first, we suspected that such grains were uranium-rich and altered, but subsequent examination under reflected light after HF etching and analysis showed that alteration was not present and that they owed their appearance to abundant fracture planes, often with visible dislocations when viewed under a scanning electron microscope (Photo 20.1). We suggest that such planes are shock induced, and are preserved in rocks in which other shock features have been removed by recrystallization, because of the inherent refractory nature of zircons. Identical zircons were found in a granitic clast in the Onaping Formation, whereas zircons from an Onaping melt rock and fluidal glass were similar but more rounded. We infer that rounding may develop in extreme cases as a result of fragments leaving exterior surfaces where fracture planes intersect. Zircon fragments adjacent to a larger grain have been observed in microprobe studies by W.V. Peredery (Staff Geologist, Inco Limited, personal communication, 1983). Current isotopic results show that all of the zircons described above are isotopically similar in having formed about 2711 Ma ago and having registered a disturbance about 1850 Ma ago. In general, the isotopic disturbance was relatively weak as most grains plot near the older age and in 2 samples,

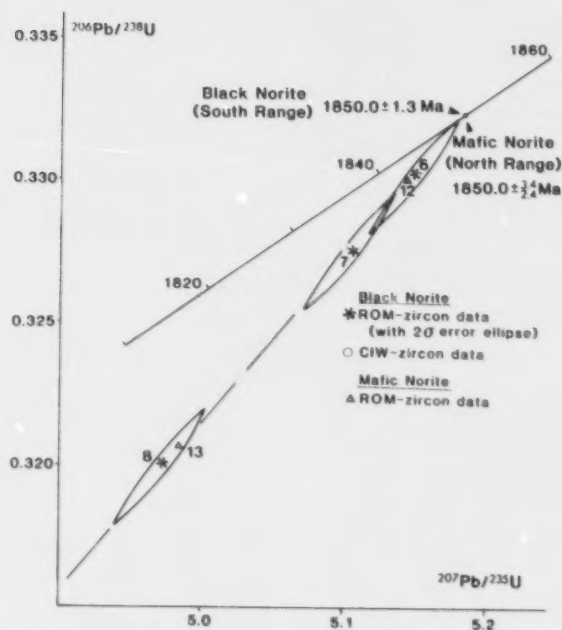


Figure 20.6. Concordia diagram with zircon data for the South Range black norite and the North Range mafic norite. The age of 1850.0 ± 1.3 Ma for the black norite is based on 6 colinear analyses, 3 of which are more than 10% discordant and are not shown in the figure. The $1850.0 \pm 3.4/-2.4$ Ma age for the mafic norite is calculated from the 2 data points 12 and 13.

the most shocked grains have been affected to the largest degree by the younger event.

Our new results contrast sharply with an early Rb-Sr whole rock study using variously shocked small granitic clasts from the Onaping Formation (Fullagar *et al.* 1971). In that study, isochrons of 1400 and 1450 Ma were obtained even though the fragments were thought to be much older and no known metamorphism took place at this time. Taken at face value, one might conclude that isotopic exchange between fragments and matrix occurred at this time in response to devitrification of the Onaping Formation glass. Large samples of Onaping Formation matrix analyzed by the Rb-Sr method provide model ages of only 1600 to 1800 Ma, and if assumed to be Archean, as the zircon results to date indicate, they must have undergone extensive isotopic exchange, not just between small clasts and matrix, but between major rock volumes and an external source of common strontium. The extent of such exchange is reduced if significant amounts of Rb were added during the formation and emplacement of the Onaping Formation. In any case, it is certain that the Rb-Sr systems present cannot be assumed to reflect those of the source region from which the Onaping Formation was created.

In our zircon study, we should note that in most cases only a single zircon fraction was analyzed from each rock, even though as much as 1 g of zircon was available from an original sample which weighed in excess of 50 kg. This was necessary because almost all

zircons present in these rocks yield data that fall below the line joining the primary and secondary ages, due to the presence of recent surface correlated lead loss. As in other studies reported here, where insufficient high quality zircons were present, we chose to reduce the sample size. In 1 case, 0.034 mg of zircon containing only 3×10^{-9} g of radiogenic lead was successfully analyzed. This selection procedure proved successful in most but not all cases as will be apparent in subsequent data.

The Levack Gneiss Complex

LOCAL PEGMATOID (3.4 km NORTH OF THE NORTH RANGE NORITE ON HIGHWAY 144, TK 82-10)

Because the Levack Gneiss Complex is very heterogeneous, we chose to sample a local pegmatoid to obtain zircons of a single age, for example, that of the last major metamorphism. One fraction of selected new growth zircons from this sample is concordant within error so that only 2 analyses were performed to define an age of metamorphic growth at 2647 ± 2 Ma (Analyses 1 and 2, Table 20.4, Figure 20.7). Analysis 1 contains very little zircon (0.045 mg) so that the total common lead present (16×10^{-12} g) provides an upper limit for our lead contamination during the analysis.

HETEROGENEOUS GNEISS (COLLECTED ABOUT 1 km NORTH OF THE NORITE, S81-2)

A single fraction of the best available grains from this sample gave data point 3, which has a minimum age of 2662 and plots near the top of the 2711 to 1836 mixing line (Analysis 3, Table 20.4, Figure 20.7).

HOMOGENEOUS GNEISS (FA 1 COLLECTED 275 m NORTH OF THE NORITE, FA 2 COLLECTED 435 m NORTH OF THE NORITE)

Zircons from 2 samples of homogeneous gneiss collected < 1 km north of the norite by Falconbridge Limited have been studied in detail (Analyses 9 to 15, Table 20.4, Figure 20.7). In these samples, zircons representing different degrees of development of the crystallographically oriented fracture planes were selected and analyzed. Analyses 9 and 10, which represent the least-cracked grains from each sample, occupy the upper end of the data array for these samples (Figure 20.7), whereas Analyses 14 and 15 represent the most highly cracked grains analyzed and occupy the lower end of the array. A single fraction (Analysis 11), contains weakly cracked grains and occupies an inter-

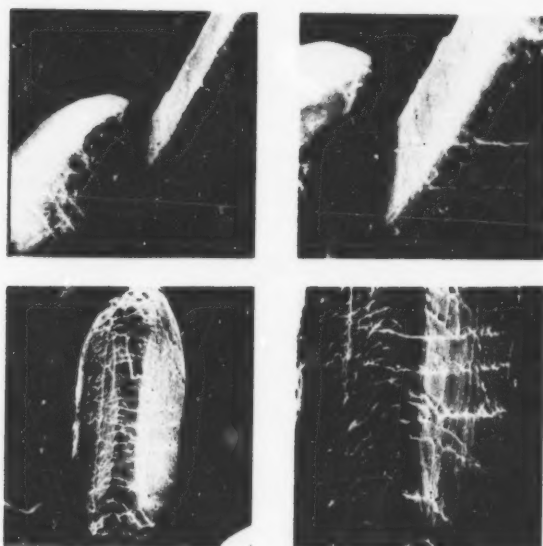


Photo 20.1. SEM photographs of shocked zircons in Levack Gneiss Complex. Shocking produced 2 sets of crystallographically oriented cracks; zircon segments are offset along the cracks and surfaces are pitted at the intersection of planes. Grains are about 100 mm thick. Pictures on the right show details of the respective zircons on the left.

mediate position. All of the grains so far discussed are +200 mesh. Two fractions of abraded -325 mesh grains were analyzed in an attempt to extend the line toward the secondary event on the usually good assumption that finer grained material would respond more extensively to this disturbance (Analyses 12 and 13, Figure 20.7). The results, however, show that the highly fractured grains, not the finest grains are the most discordant. The finer grained material has suffered a more extensive recent lead loss, indicated by the fact that the data plot slightly below the line defined by the coarse-grained fractions. It is important to note here that the usual correlation between discordance and uranium level is not followed in these samples, since the 2 least discordant fractions (Analyses 9 and 10, Table 20.4, Figure 20.7) have uranium levels of 135 and 126 ppm, respectively, while the 2 most discordant fractions (Analyses 14 and 15) have uranium levels of 127 and 153 ppm, respectively. The -325 mesh grains contain more uranium, that is levels of 228 and 274 ppm, but have intermediate discordance. This implies that the degree of discordance is related to the magnitude of the shock event and that the line itself may have been generated by shock-induced discordance, and after shock-induced heating rather than by the thermal pulse associated with the emplacement of the norite. If so, we have indirectly dated the shock event at 1836 ± 14 Ma, an age that overlaps with that of the norite, 1850 ± 1 Ma. The fact that the lower end of the line gives a slightly younger projected age than the norite is not surprising because, in general, any sample which loses a relatively large amount of lead during one disturbance can be expected to respond more to later disturbances as well. Thus, recent lead loss is more probable at the lower end of the line and the line is expected to tilt downward. The fact that other samples far from the norite conform to the same linear array supports the conclusion that the disturbance represented by the lower end of the line is shock-related rather than norite-emplacement related.

HETEROGENEOUS GNEISS FROM LEVACK MINE ROAD A FEW METRES FROM THE NORITE CONTACT, S 81-1

Unique colourless, sharply faceted, low uranium zircons occur among the rounded, shattered grains from a sample collected only a few metres from the norite contact. In general, they do not overgrow early formed crystals, and their complete lack of oriented fracture planes attest to their formation subsequent to the shock event recorded in the other grains. Isotopic results confirm this expected result as the data plots virtually at the age of the norite (Analysis 16, Table 20.4, Figure 20.7). A second sample consisting of the least-fractured grains from the "shocked" population dem-

onstrates a remarkable lack of disturbance even though the sample was subjected to a major thermal event during the emplacement of the norite (Analysis 8, Table 20.4, Figure 20.7). In this case, the data plot above the mixing line defined by the other samples, as if the majority of the grains selected grew during the metamorphic event recorded in the zircons from the local pegmatoid, 2647 Ma ago. This lack of major resetting adjacent to the norite supports the concept that the secondary age is related to the impact event, rather than the emplacement of the norite.

The Onaping Formation

GRANITIC BLOCK FROM THE TOP OF THE BASAL BRECCIA, NORTH RANGE, TK 82-14

Zircons from a granitic clast in the Onaping Formation basal breccia are morphologically similar to those in the Levack Gneiss Complex; they are rounded and variously shattered along crystallographically oriented planes. Selected crack-free grains after abrasion are relatively concordant and plot on the line defined by the Levack Gneiss Complex zircons for a primary age of 2711 ± 7 Ma and a secondary age of 1836 ± 14 Ma (Analysis 7, Table 20.4, Figure 20.7). These zircons then are both physically and isotopically indistinguishable from those in the Levack Gneiss Complex.

IGNEOUS TEXTURED MELT ROCK, BASAL BRECCIA, ONAPING FORMATION, S 81-4

The matrix of the igneous textured melt rock (described by Peredery in Guy-Bray 1972) in the North Range basal breccia, in contrast to the Levack Gneiss Complex samples, contains very few zircons. Those that are present are highly pitted, small and rounded, suggestive of destruction and abrasion of the grains during the shock event itself. This concept is supported by a cloud of small zircon fragments adjacent to a larger zircon crystal observed by W.V. Peredery (Staff Geologist, Inco Limited, personal communication, 1983). Because of the small yield, selection of favourable grains was restricted and the chance that grains with recent lead loss (plotting below the line) would be analyzed was enhanced. Of the 2 fractions analyzed, 1, the coarsest fraction (Analysis 5, Table 20.4) plots on the line and is isotopically identical to zircons from the Levack Gneiss Complex. The finer fraction from the same rock (Analysis 4, Table 20.4), plots below the line as if recent lead loss has displaced the U-Pb system analyzed from the line. As noted earlier, finer fractions are more susceptible to recent surface-related lead loss. In general, it is clear that the zircons from melt rock are relatively concordant; for

TABLE 20.4: U-Pb ZIRCON DATA OF LEVACK GNEISS AND ONAPING FORMATION.

SAMPLE	WEIGHT (mg)	U (ppm)	MEASURED $^{206}\text{Pb}/^{204}\text{Pb}$	COMMON Pb (ng)	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$ age (Ma)
Levack Gneiss—local pegmatoid (TK 82-10)									
1) + 200, cl, A, ↓	0.045	237	20613 ²	0.016 ²	0.17933	0.0866	0.5060	12.510	2646.5
crack-free									
2) + 200, cl, A, ↓ trace	0.383	273	28184 ²	0.113 ²	0.17960	0.0925	0.5038	12.451	2646.0
cracks									
Levack Gneiss—heterogeneous gneiss (S 81-2)									
3) + 200, cl, A, ↓	0.064	302	19707 ²	0.030 ²	0.18104	0.0843	0.5025	12.537	2661.5
Onaping Formation—igneous-textured melt rock (S 81-4)									
4) 200-325, cl, A	0.034	205	4601 ²	0.045 ²	0.18010	0.1534	0.4864	12.078	2653.7
5) + 200, A	0.108	194	6574 ²	0.093 ²	0.17663	0.1902	0.4834	11.738	2616.6
Onaping Formation—fluidal glass (S 81-5)									
6) + 200, M1, A	0.150	139	11110 ²	0.054 ²	0.17763	0.2020	0.4795	11.743	2630.7
Onaping Formation—granitic block (TK 82-14)									
7) + 200, cl, A, ↓	0.157	982	8615 ²	0.513 ²	0.17472	0.0265	0.4753	11.361	2590.2
Levack Gneiss—homogeneous gneiss (FA 1)									
9) + 200, cl, A, ↓ no	0.201	135	2757 ¹	0.275 ¹	0.17277	—	0.4624	10.835	2557.0
cracks									
11) + 200, A, ↓ minor	0.466	128	3883 ¹	0.418 ¹	0.16864	—	0.4500	10.314	2520.0
cracks									
12) -325, A, ↓	2.450	228	1023 ¹	14.9 ¹	0.17833	—	0.4478	10.267	2520.6
13) -325 A, ↓	1.380	274	5080 ¹	2.00 ¹	0.16793	0.1207	0.4464	10.192	2513.7
15) + 200, A, extrem.	0.232	153	1274 ¹	0.733 ¹	0.17058	—	0.4349	9.721	2478.0
cracked									
Levack Gneiss—homogeneous gneiss (FA 2)									
10) + 200, A, ↓ minor	0.784	126	3616 ¹	0.752 ¹	0.17120	0.1706	0.4556	10.567	2540.0
cracks									
14) + 200, A, ↓ extrem.	0.510	127	4248 ¹	0.400 ¹	0.16408	—	0.4363	9.740	2475.4
cracked									
Levack Gneiss—heterogeneous gneiss (S 81-1)									
8) + 200, cl, A, no	0.085	119	1900 ²	0.152 ²	0.17579	0.1201	0.4686	11.006	2561.0
cracks									
16) + 200, cl, A, new	0.237	78	24816 ²	0.015 ²	0.11421	0.1515	0.3334	5.251	1867.3
crystals									

Notes:

1) corrected for fractionation

2) corrected for fractionation and for common Pb in spike

3) corrected for fractionation, spike, and blank

4) corrected for fractionation, spike, blank, and initial common Pb

+ 200 = size in mesh; cl = clean; A = abraded; ↓ = non magnetic, magnetic on high gradient magnetic pin; M1 = magnetic at 1° tilt on Frantz isodynamic separator, all other fractions are non magnetic at 0° tilt.

example, they have not been profoundly affected during the melting event, so that the melting, quenching, and cooling of this material must have been very rapid. This concept is further supported by the fact that the melt rock contains only zircons inherited from its source, and contains no zircons grown during the melt stage, either as new crystals or as overgrowths on older grains. Volcanic rocks with this amount of inheritance, to our knowledge have never been observed, and when inherited zircons do occur in igneous rocks, both new crystals and crystal overgrowths are common.

THE FLUIDAL GLASS, BASAL BRECCIA, NORTH RANGE, S 81-5

Like the igneous textured melt rock, the fluidal glass contains very few zircons, and those which are present

are rounded and pitted. The single analyzed fraction (Analysis 6, Table 20.4) plots below the mixing line as if it had been affected slightly by a relatively recent lead loss. In general, zircons from both melt rocks and fluidal glass are relatively concordant when compared with those from the basement Levack Gneiss Complex. This may indicate rapid quenching and cooling of the Onaping Formation and a slower post impact heating and cooling in the blanketed basement.

Again, the zircons in the samples studied bear no resemblance to those from numerous volcanic suites studied in this and other laboratories, rather, the isotopic and morphological observations suggest derivation by rapid melting and cooling of an Archean basement like the Levack Gneiss Complex.

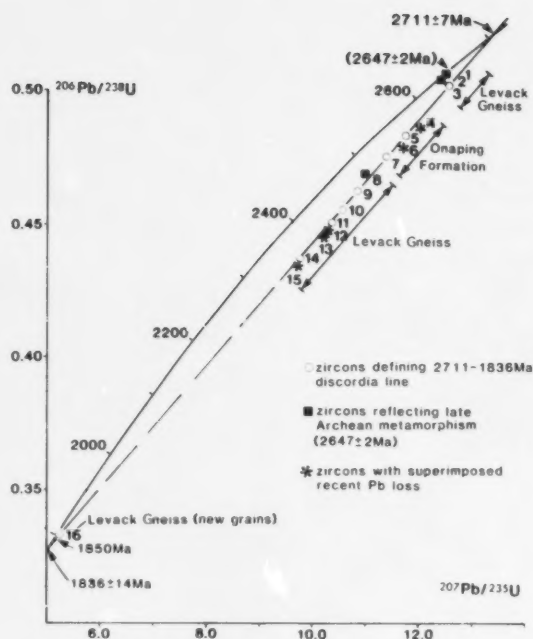


Figure 20.7. Concordia diagram with zircon data for Levack Gneiss Complex and Onaping Formation. The age of 2711 ± 7 Ma is defined by coarse-grained zircons and dates formation of the Levack Gneiss Complex. The age of 2647 ± 2 Ma is defined by concordant zircon (1) in a pegmatoid and dates late Archean metamorphism. The discordance of the zircons is unrelated to the distance of the samples from the norite, but is crudely proportional to the amount of cracking of the zircons, which is probably the result of the explosive Sudbury Event dated by the lower intercept age of 1836 ± 14 Ma. Newly formed 1850 Ma old zircons (16) are found only in a sample 3 m from the norite contact.

Summary of Levack Gneiss Complex and Onaping Formation Zircon Results

Circled points on Figure 20.7, representing samples of relatively large grain size with relatively little sign of recent lead loss, are colinear with a 33% probability of fit within experimental error. This is remarkable considering that samples of the Levack Gneiss Complex from 3 localities, composed of a granitic block from the Onaping Formation, and a zircon fraction from the igneous-textured melt rock in the Onaping Formation are included, and considering the heterogeneous nature of the Levack Gneiss Complex. We conclude from this that the Levack Gneiss Complex has a primary age of 2711 ± 7 Ma, and note that late metamorphic zircons formed 2647 Ma ago are locally present. It is further concluded that the secondary event recorded by the discordia probably represents the shock event rather than emplacement of the norite, because the most shocked grains in 2 rocks are the most reset, the samples far from the norite conform to the same discordia, the Onaping Formation zircons are relatively

concordant compared with basement zircons where post shock heating would be a maximum, and because zircons adjacent to the norite are not strongly reset. Although further sampling is required, the results to date support the concept that the Onaping Formation melt rocks were derived by partial melting of an Archean basement like the Levack Gneiss Complex, and were cooled so rapidly that new zircon growth could not occur. The complete lack of new crystal growth or overgrowths of zircons distinguishes this rock from any volcanic rock that it might resemble. These observations tend to support the meteorite impact hypothesis and origin of the Onaping Formation as a fall-back breccia.

The possibility that refractory zircons may record shock features under conditions which would remove such features from other minerals should be investigated further.

THE MURRAY PLUTON AND GRANITIC DIKES INTRUDING THE SUDBURY IGNEOUS COMPLEX

Introduction

The Murray Pluton, a granitic body exposed in an area 5 km long and 1.5 km wide, is intrusive into the lower Huronian Supergroup rocks about 3 km north of Sudbury. A similar but larger body, the Creighton Pluton intrudes the same section along the southern margin of the norite to the southwest. A U-Pb zircon age of $2333 \pm 32/-22$ Ma for the Creighton Pluton was reported by Frarey *et al.* (1982) with a lower intercept of 195 Ma.

Although the Murray Pluton is considered to be intruded by the norite, the relationships are complicated by the presence of granitic dikes which cut the norite and in some cases appear to originate in the Murray Pluton. This apparent paradoxical relationship led Collins (1936) to suggest that the norite had locally melted the granite to produce back-injection of granite into the norite.

An earlier attempt to resolve the conflicting relative ages was made by Gibbins and McNutt (1975a) using the Rb-Sr whole rock method, but in both cases the isochron data scattered outside of experimental error. If lines are passed through these data points, ages and initial ratios of 2223^{+1} Ma to 0.7211 and 1777^{+1} Ma to 0.7115 are obtained for the granite and dikes, respectively. It was suggested that the Murray Pluton was derived from remelted crust, whereas the later dikes are unlikely to represent remelted granite, and their origin is problematical.

¹Recalculation of data by present authors ($\lambda = 1.42 \times 10^{-11} \text{ a}^{-1}$).

CHAPTER 20

TABLE 20.5: U-Pb ZIRCON DATA OF MURRAY GRANITE AND GRANITIC DIKE CUTTING NORITE.

SAMPLE	WEIGHT (mg)	U (ppm)	MEASURED ¹ ²⁰⁶ Pb/ ²⁰⁴ Pb	COMMON					
				Pb (ng) ²	²⁰⁷ Pb/ ²⁰⁶ Pb ³	²⁰⁸ Pb/ ²⁰⁶ Pb ³	²⁰⁶ Pb/ ²³⁸ U ⁴	²⁰⁷ Pb/ ²³⁵ U ⁴	²⁰⁷ Pb/ ²⁰⁶ Pb ⁺ age (Ma)
Murray Granite (S-81-7)									
1) ONM, A	0.32	535	12203	0.27	0.14995	0.1724	0.4243	8.736	2338.3
2) ONM, + 200	0.62	540	6716	1.07	0.14778	0.1674	0.4061	8.187	2302.0
3) IM + 200	0.63	511	5592	1.22	0.14633	0.1685	0.4001	7.968	2281.0
Granitic dike cutting norite (S-81-8)									
4) ONM, + 200, A	0.25	1090	5020	0.95	0.11636	0.2090	0.3195	5.024	1865.0
5) ONM, -200, A	0.12	1296	4032	0.71	0.11653	0.2149	0.3187	4.996	1859.0
6) ONM, A	0.035	1301	6570	0.09	0.11338	0.2010	0.3187	4.965	1848.2
7) OM, + 200	0.33	1179	2355	2.86	0.11867	0.2115	0.3004	4.695	1853.4
8) 5M + 200	0.51	2104	640.0	25.74	0.13306	0.2333	0.2492	3.854	1835.0

Notes:

1) corrected for fractionation

2) corrected for common Pb in spike

3) corrected for fractionation, spike, and blank

4) corrected for fractionation, spike, blank, and initial common Pb

M, NM = magnetic, non magnetic on Frantz isodynamic separator at 1.7 Amp. and at indicated angle of tilt; + 200 = mesh size; A = abraded

As with other post-Archean igneous rocks in the region, both the Murray Pluton and the granitic dikes studied contain zircons which are relatively rich in uranium, making it difficult to create and isolate material that is highly concordant.

The Murray Pluton

An age of 2388 ± 20/-13 Ma with a lower intercept at 1388 Ma is based on 3 fractions of zircon from the Murray Pluton (Analyses 1 to 3, Table 20.5, Figure 20.8) (probability of fit is 10%). In this case, the best abraded fraction contains about 500 ppm uranium and is still 5% discordant, with a minimum age of 2338 Ma. The high lower intercept may reflect the thermal event recorded by the biotite K-Ar ages in the region at 1000 to 1300 Ma, as summarized by Gibbins and McNutt (1975b), or may reflect the intrusion of the norite at 1850 ± 1 Ma ago with subsequent more recent lead loss. These same events may have produced the scatter in the Rb-Sr results and their younger apparent ages. All of the U-Pb analyses are more concordant than those for the Creighton Pluton reported by Frarey *et al.* (1982), whose age may be a minimum value because of the low reported lower intercept. Our age provides a minimum age for the lower part of the Huronian Supergroup of 2388 Ma, which is compatible with the age of 2450 ± 25/-10 Ma for the Copper Cliff Formation reported in an earlier section.

The Murray Pluton samples for this study were collected only 200 m south of the norite contact (see Figure 20.4). Further studies to verify our current results using more favourable samples are required.

Granite Dike Cutting Norite

A granitic dike cutting the norite was collected in the Little Stobie Mine area about 1 km north of the contact with the norite (see Figure 20.4). Although zircons are abundant, they are highly cracked and altered as a result of their high uranium content (> 1000 ppm in all cases). The isotopic results (Analyses 4 to 8, Table 20.5, Figure 20.8) indicate a complex age population with a non-linear data array resulting from a combination of minor inheritance and a relatively extensive secondary lead loss. Analysis 4 has the largest inherited component as illustrated by its minimum age of 1865 Ma, 15 Ma older than the norite itself. The least amount of inheritance is present in Analysis 6 which, if corrected along the same lead loss trajectory exhibited by the zircons in the host norite, yields an age of 1855 Ma. We conclude that the dikes were very likely emplaced shortly after cooling of the norite, and that they contain only a small amount of inherited zircon, and therefore, were not derived by complete melting of the Murray Pluton.

DISCUSSION AND CONCLUSIONS

Intrusion of the Levack Gneiss Complex at 2711 ± 7 Ma is similar in age to Kenoran igneous activity elsewhere in the Superior Province. The syenite areally associated with the East Bull Lake Gabbro-Anorthosite Intrusion shows that Archean igneous activity extended to at least 2665 ± 1.6/-1.4 Ma in this region, while the 2647 ± 2 Ma on a pegmatoid from the Levack Gneiss Complex dates late Archean metamorph-

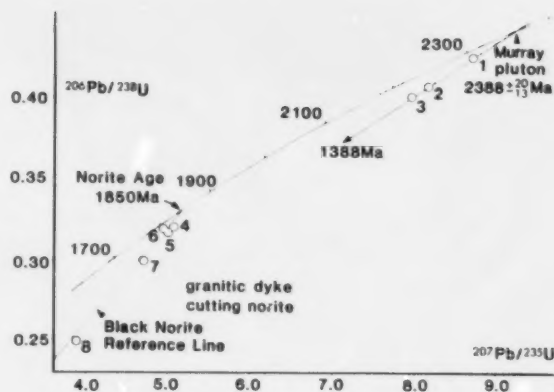


Figure 20.8. Concordia diagram with zircon data for the Murray Pluton and a granitic dike cutting the norite. The age of $2388 \pm 20/-13$ Ma is defined by 3 colinear analyses, and dates intrusion of the Murray Pluton. Data points in the granitic dike are scattered, reflecting small amounts of inheritance superimposed by complex Pb loss; the dike intruded probably shortly after 1850 Ma, the age of the norite.

ism. Similar metamorphic ages have been measured in adjacent parts of the Superior Province (Krogh and Turek 1982; Percival and Krogh 1983).

Mafic intrusions associated with the lower part of the Huronian Supergroup have been dated at 2491 ± 5 Ma and $2480 \pm 10/-5$ Ma. An age of $2450 \pm 25/-10$ Ma has been determined for the overlying Copper Cliff Formation. Thus, Huronian igneous activity began over 150 Ma after the close of the Archean. The Huronian Supergroup was subsequently intruded by granitic stocks such as the Murray Pluton at $2388 \pm 20/-13$ Ma. This was followed by the Nipissing Diabase after another gap of more than 200 Ma (Van Schmus 1965).

Finally, the area was affected by a major explosive event which produced the Onaping Formation breccia and culminated in intrusion of the Sudbury Igneous Complex. Detailed analysis of various phases of the Complex indicates that the intrusion was rapidly emplaced, probably within 1 Ma. The mean age of the norite samples is 1850 ± 1 Ma. The lower intercept age of zircons from the Onaping Formation and shocked samples of the Levack Gneiss Complex is 1836 ± 14 Ma. This value may be biased downward slightly due to secondary lead loss. The relationship between lead loss and fracturing indicates that the zircons were partly reset by shock metamorphism. Therefore, the data suggest that the explosive event preceded intrusion of the Sudbury Igneous Complex by a short time.

The nature of the event, whether meteor impact or volcanic eruption, cannot be determined from the zircon data, but there are several observations which tend perhaps to favour the impact hypothesis:

1. All ages thus far measured from rocks associated with the Sudbury "Event" agree within error. The

"Event" appears episodic with no immediate igneous precursors.

2. Zircons from the Onaping Formation breccia seem entirely derived from country rock and give no evidence of any component newly grown in a magma chamber.

3. Zircons from country rock adjacent to and within the Sudbury Igneous Complex display parallel fractures which are unique in our experience, and which we interpret as shock-metamorphic features.

It should be noted, however, that the area has undergone a continuous history of intermittent magmatic activity from the late Archean to the intrusion of the Sudbury Igneous Complex, and that it occupies a rather unique position near the junction of 3 provinces and 2 pre-existing fault systems (Card and Hutchinson in Guy-Bray 1972). One notable feature is that zircons from all post-Archean rocks which we have studied in this area are anomalously high in uranium.

If the impact hypothesis is valid, it is perhaps the coincidence of such an impact occurring in a geologically active area which produced intrusion of the Sudbury Igneous Complex and base-metal mineralization.

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ORIGIN OF THE SUDBURY STRUCTURE

The Origin of the Sudbury Structure

Introduction

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Up until some 25 years ago, geoscientists considered that any geological process must have an endogenic origin or an origin related to physical or chemical processes occurring at the surface of the earth. Therefore, during the first 80 years of geological research in Sudbury, that is up to the early 1960s, scientists looked for an endogenic model to account for the geological features observed in Sudbury. Geologists working in Sudbury were agreed that the Sudbury Structure originated by volcanic or volcano-tectonic processes, and that the heterolithic breccias of the Onaping Formation and the brecciation of the Footwall rocks around the Structure were accounted for by these processes. Geologists also agreed that the initial process forming the Sudbury Structure had been a powerful, endogenic explosion, and that the intrusion of the Sudbury Igneous Complex and the emplacement of the nickel-copper orebodies followed this explosion.

In the 1960s and early 1970s, the study of meteorites and known terrestrial impact craters, shock wave studies, shock experiments, and increasing research on shock-induced mineral deformation drew the attention of geoscientists to shock-metamorphic processes.

This led to a wealth of new information not hitherto appreciated by geologists working in Sudbury.

In the early 1960s, R.S. Dietz proposed an impact origin for the Sudbury Structure. Since then, there has been vigorous debate for or against Dietz's proposal. Proponents of the impact theory base their idea on experimental and field evidence and interpretation. Proponents of an endogenic origin point out that many observations cannot be accounted for by a meteorite impact origin. It has also been suggested that the Sudbury Structure may be an impact-induced volcanic centre.

In the following 3 papers, the observations described in this volume are interpreted according to each school of thought. The reader may thus critically weigh the evidence for or against either theory, but will probably come to the conclusion that far too many questions remain unanswered to allow a definite choice. Much work has still to be done on the Sudbury Structure. It is hoped that the following 3 accounts will stimulate discussion and lead to the initiation of new research programs.

CHAPTER 21

The Sudbury Structure: Considerations and Models for an Endogenic Origin

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ABSTRACT

There are several factors which justify the consideration of an endogenic model for the Sudbury Structure, which is a cryptoexplosion structure. Several requirements for proof of meteorite impact have not been, or cannot be met. Most features of the Sudbury Structure can readily be explained through endogenic processes. The presence of shock metamorphism related to the Sudbury Structure cannot be used as singular proof of impact, and several possible examples of endogenic shock metamorphism attest to this. Fortuitous geological relationships, required for an impact origin, are too numerous to be accepted without considerable reservation.

The Sudbury Structure was never circular or nearly so; this is based on several structural relationships of the Sudbury Structure with its surrounding geological units. The Sudbury Structure is spatially and/or temporally related to crustal features such as: the Great Lakes Tectonic Zone-Murray Fault Zone; the Grenville Front Boundary Fault; a large-scale curvilinear positive gravity anomaly; large elongate positive magnetic anomalies, the Wanapitei (cryptoexplosion) Structure, gneisses and migmatites, granitic plutons, and Huronian outliers. Some of these relationships are likely genetic. The Archean medium- to high-grade gneisses and downfaulted outliers of Huronian units, both of which are subconformable to the Sudbury Structure, were essentially tectonically in place before the Sudbury Events.

The Sudbury Structure is genetically associated with large volumes of volcanic rocks present as the Onaping Formation, and plutonic rocks present as the Sudbury Igneous Complex. One or more large intrusions are inferred from geophysical data to underlie the Sudbury Structure. The Melt Bodies of the Onaping Formation are related to plagioclase-rich granophyre of the Sudbury Igneous Complex.

Several major types of volcanic/plutonic structures have some features similar to those of the Sudbury Structure. No single type is clearly analogous to the Sudbury Structure, and none is known to be associated with shock metamorphism. Differences of the individual structures compared to the Sudbury Structure can be attributed to: processes that produce endogenic shock metamorphism and, consequently, unusual features; and superposition of 2 or more

types of structures during the complex development of the Sudbury Structure. Endogenic shock metamorphic processes remain enigmatic. Favourable processes for the Sudbury Structure fall into the class of diatremes. A mantle hot spot may be associated with the initiation and/or continuation of the Sudbury Events.

Two proposed models, considered in a spectrum of solutions, reflect the complex history of the Sudbury Structure and uncertainties regarding various geological relationships in the Sudbury area. One model invokes deep crustal release of gas which rises to create surface explosions followed by volcanism in various stages and concomitant or post-volcanic plutonism. The other model invokes volcanic rocks as precursors to the Onaping Formation, followed by large-scale explosive brecciation of these volcanic rocks, and subsequent volcanism and plutonism. The models by their very nature draw attention to aspects which require further research.

The origin of the Sudbury Structure remains unproven. All aspects relevant to Sudbury geology and geology in general, that are known or interpreted, must be taken into account when evaluating any particular model or origin for the Sudbury Structure. The difficult task we face is to recognize what is relevant and what is known, given the dynamic state of our knowledge.

INTRODUCTION

In the past, there have been 2 main theories on the origin of the Sudbury Structure: endogenic or volcanotectonic (Burrows and Rickaby 1930; Thomson 1957; Williams 1957; Speers 1957; Stevenson 1961, 1972); and meteorite impact (French 1970, 1972b; Dence 1972; Peredery 1972a, 1972b). A third, subordinate theory involves impact-induced volcanism (Dietz 1964; Thomson 1969). Previously, the author has supported both a volcanic origin (Muir 1981) and an impact-induced volcanic origin (Muir 1982, 1983) for the Onaping Formation. Here, however, the author presents endogenic models for the Sudbury Structure. The main question that may be asked is "Why consider a purely endogenic origin for the Sudbury Structure at

all?" A number of points covered in the following sections justify this approach. Many things about Sudbury geology are not known, and thus this paper cannot prove an endogenic origin. It does, however, present evidence, based on our present knowledge, that conflicts with an impact origin and supports an endogenic origin.

PROBLEMS WITH THE IMPACT MODEL

General Impact Model

Problems with the general model for large-scale impacts are manifold:

1. there are no first-hand observations
2. there are natural constraints to modelling them
3. there is a reliance on the hypothesis that shock metamorphism can only be produced naturally by hyper-velocity meteorite impact
4. there is a tendency to interpret all features at cryptoexplosion sites as the immediate result of impact processes.

The first 2 points are also common to any endogenic models for cryptoexplosion structures. Cooper (1977) listed 28 inter-related, complex variables in impact cratering mechanics alone, many of which are indeterminable. Melosh (1980) stated that there is no fundamental understanding of the phenomena exhibited by complex impact craters.

The general absence of shock-metamorphic features in a "normal" volcanic environment may be because: volcanic rocks commonly consist of glassy, vesiculated, and/or fragmental material which may not respond to a shock wave in the same manner as do granitoids or lithified sediments commonly found at cryptoexplosion sites; and processes capable of producing shock metamorphism may not operate in, or be directly related to, these environments. The requests for cautious qualification of interpretation and extrapolation of experimental results on shock metamorphism presented by Carter (1965), Chao (1967, 1968), DeCarli (1968), Stöffler (1971), and Currie (1971a) should be heeded.

Many features at cryptoexplosion sites are not readily explainable by impact processes as modelled or as interpreted from proven impact sites. Such features include large volumes of massive igneous-textured rocks, extremely thick overturned sequences surrounding the structure, and cross-section and plan view configurations. The variables and varieties of products involved with endogenic origins are probably much greater in number than for an impact origin.

If any of the above features are the result of endogenic processes in any cryptoexplosion structure,

then significant modifications of the general impact model would be necessary. Detailed *in situ* observations required for positive identification of the origin of any structure or its component features have not been made on any extraterrestrial body. Therefore, interpretation and extrapolation of lunar and planetary crater features must be viewed with some caution.

Impact Model for the Sudbury Structure

Several serious drawbacks are inherent in the impact model for the Sudbury Structure. These are: the requirement for shock metamorphism to be impact related; the requirement for only 1 associated shock event; the wide range in orientation of shatter cones; the requirement of an initially circular structure; the unique structural and geological setting of the Sudbury Structure, the genetically associated volcanic and plutonic rocks of the Sudbury Structure; and the unacceptably high number of required fortuitous relationships for an impact. Failure to meet any of these requirements, or to account for the above points is a basis on which to seriously consider an endogenic origin. In addition, the published estimates and assumptions of speed, diameter, density, material, and hence volume and kinetic energy of the proposed impacting bolide, as well as the dimensions of the resultant crater and volumes of melt material produced vary greatly (compare with Deitz 1964, 1972; French 1968, 1970, 1972a; Dence 1972; Peredery and Morrison, Chapter 22, this volume). The variations are of such a magnitude that in the author's opinion, the data cannot be the basis for a valid attempt to model the Sudbury Structure as an astrobleme.

The following section deals with the above drawbacks in light of an endogenic origin for the Sudbury Structure.

FAVOURABLE ASPECTS FOR AN ENDOGENIC ORIGIN

Endogenic Shock Metamorphism

There needs to be only one exception to the concept that shock metamorphism requires a meteorite impact to make the rigorous relationship invalid. Also, there should be only 1 shock event related to a given impact structure with the exception of direct impact-on-impact. Several examples of possible endogenic shock features exist on Earth.

The Vredefort Structure in South Africa is the largest terrestrial cryptoexplosion structure. Simpson (1981) and Lilly (1981) have presented evidence that 2 shock events have affected the collar rocks of this structure. Simpson showed that shatter cones trans-

gress the fragments and matrix of fault breccias associated with previously overturned collar rocks presumed to be the result of impact (Dietz 1961, 1962). Lilly argued that the first shock event was separated from the second by a period of thermal recrystallization followed by large-scale deformation. This interpretation requires further study. Bisschoff (1982) recognized 2 periods of high-grade metamorphism in the structure. Schreyer (1983) maintained meteorite impact is precluded because of: space and time coincidence between the high temperatures of static metamorphism, the shock metamorphism, and the pseudotachylite brecciation; and the substantial depth of formation of the highest shock intensity. The Vredefort Structure is most likely a cryptovolcanic structure and not an astrobleme.

Various units on the Slate Islands in Lake Superior, Ontario, display shatter cones and planar features in quartz crystals. Sage (1978, 1980a, 1980b) has presented evidence that the shatter cones are spatially related to diatreme dikes and suggests they were endogenically produced. Halls (1979) and Robertson and Grieve (1979) argued for an impact origin for the shock features. An impact model for this structure would, out of necessity, make the Slate Islands structure the only known astrobleme where, through a cratering process, the central area of what would have been the crater is now significantly higher than the entire surrounding area.

The Köfels Structure in Austria is young and lacks the physiographic form of an explosion crater (McCall 1979). Here, there are glassy, inclusion-laden, dike-like, pseudotachylitic bodies with features such as lechatellierite rimming quartz xenocrysts, feldspar glass rimming fragmented feldspar crystals, and melted biotite (Englehardt 1972). Planar features in quartz and diaplectic glasses of quartz and feldspar are also present (Storzer *et al.* 1971). Although this structure has been interpreted to be an impact site, Preuss (1971) supported a landslide origin for the pseudotachylite and this has gained favour with many current workers (Burkhard O. Dressler, Geologist, Ontario Geological Survey, personal communication, 1983). The origin of the structure, however, is still unproven.

High-pressure polymorphs of silica, namely coesite and stishovite, are commonly considered by association as proof of impact, although it is known that these polymorphs can be experimentally created under static pressure conditions (Chao 1967, 1968; French 1968; DeCarli 1968; Stöffler 1971). However, coesite is reported from exposed units of high-grade blueschist facies pyrope-quartzite from the Dora Maira massif in France (Chopin 1984) and in eclogites from Norway and the South Urals (*see* Chopin 1984). Chopin ruled out the role of any meteorite impact by lack of any supporting evidence and discussed the possibil-

ity that some aspects of plate tectonics have to be significantly modified.

The above examples provide some evidence for likely and possible examples of endogenic shock metamorphism, of multiple shock events at a given structure, and alternative possibilities of producing shock-like features. The last example provides evidence that some features may not require the high-peak-pressure shock waves generally considered in order to be produced. There are numerous ways to fuse material and there may be more than one way of attaining conditions which lead to the formation of diaplectic-like features and polymorphs of minerals.

The establishment of the Vredefort Structure as a likely endogenic structure is relevant to the Sudbury Structure because: the pseudotachylites and recrystallized basement rocks in the Vredefort Structure are very similar to Sudbury Breccia and to Footwall Breccia and Footwall rocks of the Sudbury Structure, respectively (*compare with* Schreyer 1983; Schwarzman *et al.* 1983; Dressler, Chapter 6, this volume); and both structures are spatially related to high-grade metamorphic rocks (*see* section on Structural and Geological Setting of the Sudbury Structure).

There has been no evidence presented for only 1 shock event for the Sudbury Structure, but there is no clear evidence of multiple shock events either. However, there is good evidence for multiple explosive events during the formation of the Onaping Formation (Discussion of the Onaping Formation by T.L. Muir in Chapter 7, this volume; *see* section on Volcanic and Plutonic Rocks Associated with the Sudbury Structure). Additionally, such a diverse orientation of shatter cones exists around the Sudbury Structure, including the relatively undeformed North Range Footwall rocks, that multiple shock events can be considered a possibility. The shatter cone orientations are likely controlled by bedding (Guy-Bray 1966) which was not horizontal at the time of the shock event(s) (Dressler, Chapters 4 and 6, this volume; Card *et al.*, Chapter 2, this volume). The orientations do not support the concept of the simple, single-source impact model (*compare with* Manton 1965; Guy-Bray 1966; Dietz 1968; Milton 1977) for the Sudbury Structure (Dressler, Chapter 6, this volume).

The Shape of the Sudbury Structure and Sudbury Igneous Complex

The Sudbury Structure is a cryptoexplosion structure and its present shape is crudely elliptical (Figure 21.1). Some deformation of the structure has occurred, thus it is important to consider its original shape. An essentially circular shape is required for an impact crater with the exception of post-crater modification to produce a somewhat polygonal-shaped crater. The circu-

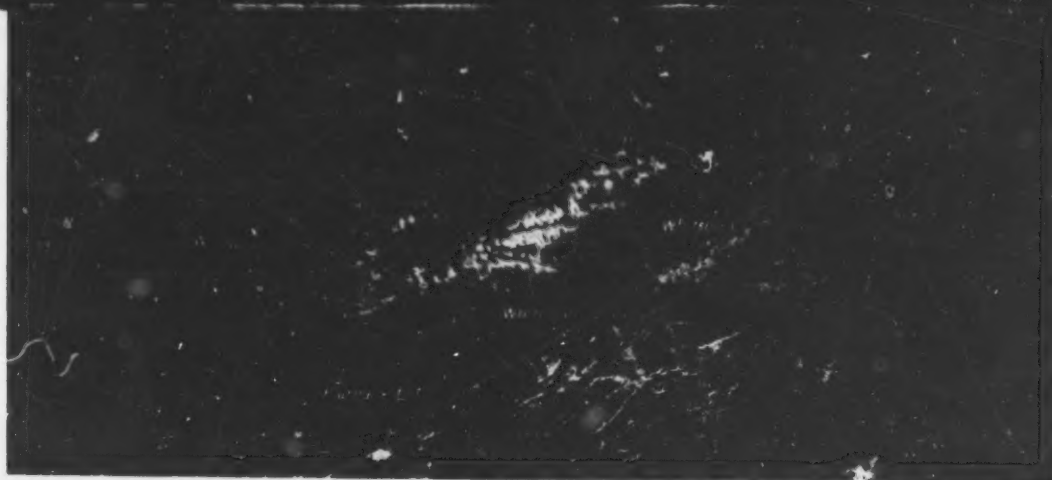


Figure 21.1. Landsat photograph of the elliptical Sudbury Structure. Wanapitei Structure lies within Wanapitei Lake. Grenville Front Boundary Fault is evident in the photograph, about 18 km southeast of Whitewater Lake.

larity of the structure can be qualitatively and semi-quantitatively tested using a simple model as shown in Figure 21.2. The circumference of the elliptical Sudbury Structure has been transposed to form a circle and a reference point was chosen approximately halfway along the North Range (*see* figure caption for Figure 21.2). For simplicity, it is assumed that the centre of the North Range has not been displaced in a northerly direction; any such displacement would not notably affect the interpretations. The Offset Dikes are drawn in hypothetical original positions radially and concentrically to the circle according to the impact model of Offset Dikes (*compare with* Grant and Bite, Chapter 12, this volume). It is assumed the Sudbury Igneous Complex is largely conformable to the original "crater" structure because of the relationship and distribution of the various Footwall Breccias and shock-metamorphic features to the Sudbury Igneous Complex (*compare with* Dressler, Chapter 6, this volume; Peredery and Morrison, Chapter 22, this volume).

The model does not take into account any crustal shortening by reverse faulting in the Murray Fault Zone, the effects of an uplifted South Range, or the decrease in diameter from that of the original crater, due to overall erosion. Any such crustal shortening would not contribute to the formation of an ellipse *per se*. Souch, Podolsky *et al.* (1969) proposed that uplift of at least 5 km of the South Range relative to the North Range has occurred, but details of this determination have not been published. The author suggests that the configuration of the Sudbury Igneous Complex and the Whitewater Group indicates much less uplift. The elliptical shape of the Sudbury Igneous Complex would probably not be possible with 5 km uplift considering the inwardly dipping Footwall contacts. Likewise, internal contacts within the Onaping Formation do not support the expected difference of unit thicknesses between the North and South Ranges.

To deform the hypothetical circular crater to the present elliptical shape requires significant crustal shortening, estimated to be in excess of 60% considering both ductile deformation and faulting to have occurred as post-Sudbury Events. The author concludes

that the structure, that is, the crater, could not have been circular or nearly so initially, because:

1. Most folding in the South Range was pre-Sudbury Events (Dressler, Chapter 4, this volume; Card *et al.*, Chapter 2, this volume) as indicated by the sub-vertical to vertical orientation of Sudbury Breccia dikes (in both North and South Ranges) and the essentially undeformed vertical to subvertical Offset Dikes.
2. The Huronian metavolcanic and Huronian metasedimentary rocks of the South Range Footwall rocks (*see also* Figure 21.5), which are now essentially conformable to the Sudbury Structure, would have had to be conformable to the circular crater which formed after the units were deposited.
3. The shape of the North Range, largely subparallel to the South Range, would require extensive deformation of the North Range Footwall rocks; this is not evident from structures in the field.
4. The sub-concentric distribution of the Cobalt Group/Quirke Lake Group boundary in the Huronian outliers would require deformation of the Superior Province, along with the Sudbury Structure, some 20 km to the north and northwest which is not indicated by field evidence.
5. The required folding to form the embayment in the Sudbury Structure in its northeastern corner is not evident in the Footwall rock unit trends and is not supported by paleomagnetic data (Morris, Chapter 19, this volume).
6. The shape of the East Range cannot be a result (*compare with* Rousell, Chapter 5, this volume; Peredery and Morrison, Chapter 22, this volume) of a 37 Ma, interpreted, meteorite impact which formed the Wanapitei Structure (Dence and Popelar 1972; Winzer *et al.* 1976), because there is no field evidence (for example, brecciation or shock metamorphism) in the Footwall rocks and Sudbury Igneous Complex to account for such massive crustal displacement.
7. The Offset Dikes would have had to be collectively rotated in a variety of directions and amounts ranging from clockwise to counterclockwise.

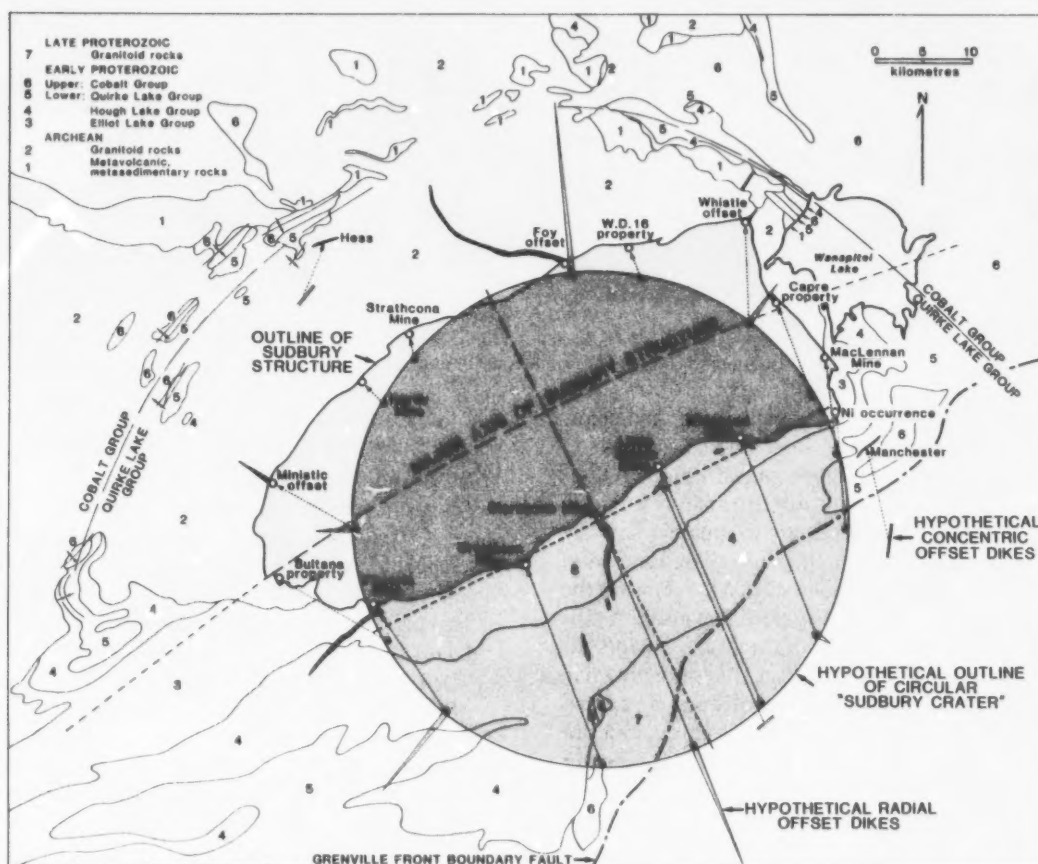


Figure 21.2. Reconstruction of hypothetical circular Sudbury crater. Circle has circumference equivalent to that of present Sudbury Structure and is located so that equivalent lengths of Footwall contact exist outside of the circle to the northeast and northwest. Stylized hypothetical offset dikes are drawn radial and tangential to circle at equivalent positions along circumference. Dotted lines show resultant vector path of selected points from hypothetical position to present location. Major lithologic units are shown for Superior and Southern Provinces. General trend of Cobalt Group (upper Huronian)/Quirke Lake Group (lower Huronian) contact shown by long dashes. Synclinal axes of outliers as indicated. See text for interpretation.

8. The Foy Offset Dike would require a substantial difference in deformation of its northern tip relative to its base which is incompatible with field evidence.

Additional constraints on the form of the Sudbury Structure have been established by others with evidence from:

1. paleocurrent orientations which indicate that the Sudbury Basin was elongate during the deposition of the Chelmsford Formation turbidites (Cantin and Walker 1972; Rousell 1972)
2. paleomagnetic measurements which show the basin was elliptical at the time of crystallization of the norite, and that it has since undergone substantially less deformation than is generally postulated (Morris, Chapter 19, this volume)
3. finite strain considerations of concretions and fragments within the Chelmsford and Onaping Formations, respectively, that, contrary to interpretations by Brocoum and Dalziel (1974), suggest the Sudbury Basin was neither circular nor almost circular prior to deformation (Rousell, Chapters 5 and 8, this volume)
4. the configuration of olivine diabase dikes and other rock relationships that indicate the Grenville Orogeny was not responsible for notable ductile deformation of the Sudbury Structure (Card *et al.*, Chapter 2, this volume).

The presence of shatter cones surrounding the Sudbury Structure cannot be used to establish a larger initial crater before erosion. Shock waves emanating from a point source or several point sources travel in all directions and would effect the country rocks around (that is, outside) the structure. Deformation of the Sudbury Structure had likely occurred at least by 1.5 Ga if not 1.75 Ga (Sims *et al.* 1981) and most erosion of the Sudbury Structure would be subsequent to this. Sub-greenschist facies metamorphism of the North Range (Card 1978) limits the amount of erosion that could have occurred to several km at the most. Any

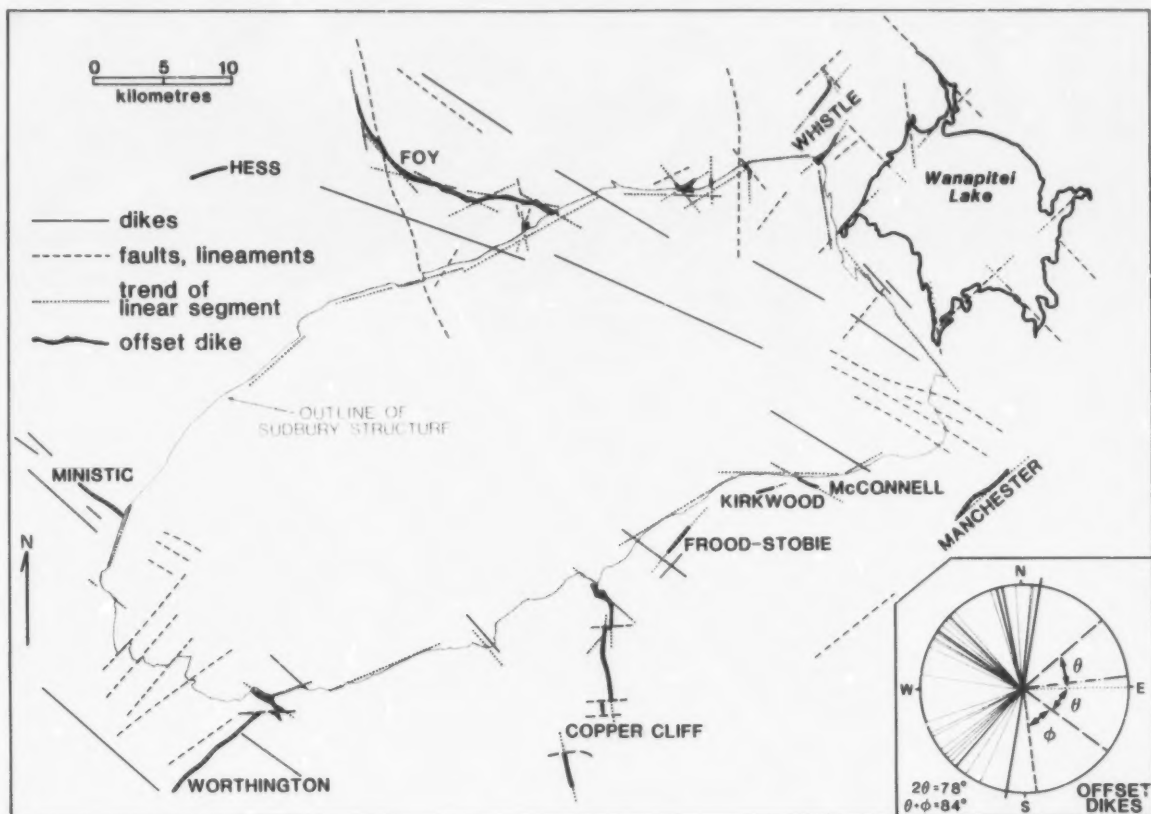


Figure 21.3. Trends of offset dike segments and nearby faults, lineaments, and dikes. Linear segments of the outline of the Sudbury Igneous Complex are also approximated. Inset shows plot of all linear offset dike segments (left half) indicated in main diagram and average trends of 3 clustered directions (right half) (dashed lines). The bisectrix of the 2 dominant trends (northeast, northwest) is shown (dotted). Right angle to subordinate trend (almost north) is also shown (dot-dash). See text for interpretation.

apparent decrease in diameter of the Sudbury Structure from erosion would be directly related to the moderately steep 45° dip of the Footwall contact of the North Range and the much steeper dips of the South Range. The decrease is too small for circularity.

With respect to the orientation of the Offset Dikes, Figure 21.3 shows an alternative possibility to the radial and concentric hypothesis. The Offset Dikes have been approximated as being composed of linear segments where possible. Their trends, which have been plotted and shown in the inset, define 2 dominant trends and 1 subordinate trend. The subordinate trend approximates the obtuse bisectrix of the dominant trends. Also plotted are selected lineaments, faults, and dikes of all ages, which lie parallel or subparallel to nearby Offset Dike segments. Based on the present analysis, the author suggests that the Offset Dike orientations could largely have been controlled by relatively large-scale crustal fracture systems. The systems for the most part were independent of the Sudbury Structure and may have partly controlled, as indicated by the trends, the outline of the Sudbury Structure. The northwest trend, later occupied by olivine diabase

dikes, likely represents a reactivation of a previously developed crustal fracture system, which has an orientation somewhat restricted to the Sudbury-Cobalt region (compare with Ayres *et al.* 1971). The above presentation is a preliminary examination of possible brittle fracture/structural relationships and requires further work, such as timing of fractures/dikes, for confirmation.

Structural and Geological Setting of the Sudbury Structure

Several studies (for example, Card *et al.*, Chapter 2, this volume; Card and Hutchinson 1972; Card 1978) have shown that the Sudbury Structure is in a unique position, spatially and temporally associated with particular rock units, major structural features, and Early Proterozoic orogenesis (Figures 21.4 and 21.5; Table 21.1). On a large scale (Figure 21.4), the Sudbury Structure lies on the northern margin of the Great Lakes Tectonic Zone-Murray Fault Zone (Sims *et al.*

TABLE 21.1: SELECTED CRYPTOEXPLOSION STRUCTURES AND THEIR RELATIONSHIPS TO TECTONIC FEATURES.

MAIN STRUCTURE	SUBSIDIARY FEATURES
Sudbury Structure (Ontario)	• part of east-northeast-trending structures and geophysical anomalies (see Figures 21.4, 21.5) • from westernmost to easternmost: • Sudbury Structure (SS) —is crudely elliptical, somewhat deformed; now 60 km by 25 km (see section on The Shape of the Sudbury Structure and Sudbury Igneous Complex) —is defined by a large, crudely layered igneous body, Sudbury Igneous Complex (SIC), with a central basin (Sudbury Basin) containing intrabasin breccias and sedimentary rocks (Whitewater Group) (see section on Volcanic and Plutonic Rocks Associated with the Sudbury Structure) —is spatially related to older anorthositic gabbros, granitoid plutons, high-grade gneisses, and diabase sills and dikes (see section on Structural and Geological Setting of the Sudbury Structure) —is spatially related to Huronian metasedimentary rocks (south, northeast) and preserved down-dropped outliers (northwest) with overall younging away from the SS (see section on Structural and Geological Setting of the Sudbury Structure) —has shock metamorphosed fragments in Footwall Breccias, SIC, and Onaping Formation breccias (see section on Endogenic Shock Metamorphism and Possible Mechanisms for Endogenic Shock Metamorphism) —corresponds to positive magnetic and gravity anomalies (Card <i>et al.</i>, this volume; Gupta <i>et al.</i>, this volume) (see section on Structural and Geological Setting of the Sudbury Structure) —lies on regional curvilinear gravity anomaly —lies on line with 1 and possibly 2 other elongate magnetic anomalies (Lake Temagami; Reservoir Decelles) —lies on northern margin of major, parallel Great Lakes Tectonic Zone (GLTZ) and Murray Fault Zone (MFZ) (see section on Structural and Geological Setting of the Sudbury Structure) —lies north of major, subparallel Grenville Front Boundary Fault (GFBF) (see section on Structural and Geological Setting of the Sudbury Structure) • Wanapitei (cryptoexplosion) Structure (see sections on Structural and Geological Setting of the Sudbury Structure and Volcanic and Plutonic Rocks Associated with the Sudbury Structure) —is crudely circular, 7.5 km diameter; allochthonous breccias with shock features; formed about 37 Ma ago (Dence and Popelar 1972; Winzer <i>et al.</i> 1976) —lies adjacent to SS on the extension of its axis and is crudely conformable to the 'concave' East Range —lies almost between the SS (to west-southwest) and Lake Temagami magnetic anomalies (to east-northeast) • Lake Temagami magnetic anomaly —crudely elliptical; slightly larger and more intense than positive magnetic anomaly of SS —axis parallel to and on line with SS anomaly; to north of and parallel to GFBF • underlies Cobalt Embayment (Huronian sedimentary cap) • Reservoir Decelles (Quebec) magnetic anomaly —about 200 km east-northeast of Lake Temagami anomaly —crudely elliptical; about same size as Lake Temagami anomaly; less intense; to north of and parallel to GFBF
Vredefort Structure (South Africa)	Bushveld—Great Dyke Lineament (Cousins 1959; Sharpe <i>et al.</i> 1981) • lineament connects 4 igneous structures—(north to south) (Bucher 1963; McCall 1979) 1) Great Dyke 2) Bushveld Complex—lies in centre of Transvaal Basin —has Pretoria Salt Pan explosion crater lying where the projection of the lineament passes through 3) Vredefort Structure—lies in centre of Witwatersrand Basin 4) Trompsburg Complex • Vredefort core—diameter 40 km —consists of high-grade Precambrian granitoid rocks uplifted about 13 km relative to "collar." —collar—17 km thick overturned metamorphosed sedimentary and volcanic rocks; shock metamorphosed twice (see section on Endogenic Shock Metamorphism) —beds face away from core One of 8 distinct geological structures aligned along a 640 km stretch of an east-trending structural zone—Rough Creek Fault Zone (Snyder and Gerdemann 1965; McCall 1979) • centred on north-northeast-trending Mississippi Embayment fault system • individual structures (westernmost to easternmost): 1) Rose Dome—3 domes along northwest-trending lineament; basement granite blocks; contact metamorphism, alteration; maximum diameter 9.4 km —associated alkaline rocks 2) Weaubleau disturbance—5 km diameter brecciated zone in intensely upfaulted zone 11 km by 5 km; breccias and unique 'conglomerates' —affinities with Decaturville, Crooked Creek, and Avon structures
Crooked Creek Disturbance ^a (Missouri)	

1980), either or both of which were active before, during, and after the Sudbury Events as shown by several episodes of igneous and metamorphic events (Card 1978). It lies north of and subparallel to the Grenville

Front Boundary Fault. It also lies west of the Ottawa-Bonnechere graben which contains alkalic complexes and the Brent Crater (cryptoexplosion crater) which formed after the Sudbury Events (Table 21.1).

TABLE 21.1: Continued.

MAIN STRUCTURE	SUBSIDIARY FEATURES
	3) Decaturville disturbance—5.5 km diameter; uplifted core; breccias, breccia dikes, shatter cones 4) Hazel Green Creek structure—reported "ash" layer, with shattered quartz grains, beneath Cambrian sandstone 5) Crooked Creek disturbance—5.3 km long elliptical structure; vertical uplift and dropdown; ring syncline and anticline; shatter cones —at intersection of 2 fault systems and aligned to one of them 6) Furnace Creek volcanic centre—2.5 km diameter; funnel-shaped tuffsite crater; at intersection of faults 7) Avon Diatremes—78 pipes in 18 km long oval cluster; some alkalic rocks 8) Hicks Dome—16 km diameter; circular uplift associated with pipes, breccia dikes, and lamprophyres at depth 9) Middlesboro structure—6.4 km diameter; lies 400 km to east of Hicks Dome on same trend —shatter cones, ring syncline, breccias
Serpent Mound Disturbance (Ohio)	• 8 km diameter; shatter cones; 3 structural units (Reidel <i>et al.</i> 1982) 1) central uplift, radiating anticlines, high angle faults, grabens 2) ring graben with doubly plunging, fault-bounded synclines and basins with concentric axes 3) transition area with concentric and radial faults and folds • structure—lies on pre-existing northwest-trending fault zone—2 periods of deformation in the structure —lies on northwest-trending regional gravity and magnetic anomalies —lies near Grenville Front —lies on a line which parallels northeast-trending faults and joins the Howell, Dycas, Flynn Creek (and Serpent Mound) disturbances
Brent Crater (Ontario)	• Brent Crater —4 km diameter; contains breccias with shock-metamorphic features, "glassy" bodies, and above average alkali content (Currie 1989) —lies within Ottawa—Bonnechere graben which may extend to Grenville Front Boundary Fault near Sudbury (Sims <i>et al.</i> 1980) —lies virtually in line with 4 alkalic intrusions with corresponding positive magnetic anomalies in Lake Nipissing; line trends parallel to the graben margins (Figure 21.4) —age of alkalic bodies (collectively) is about 580 ± 40 Ma (Easton, in press) —age of Brent Crater is 450 ± 40 Ma (Grieve <i>et al.</i> 1977)
Richat Crater (Mauretania)	• One of 4 circular structures which form a north-northeast trend (McCall 1979) • north to south: 1) Temimichat—500 m diameter crater in granite; no lava; negative gravity anomaly 2) Tenoumer—1.8 km diameter crater with associated lava; concentric dikes with shocked xenoliths form outer ring —sits aside a northeast fracture line; negative gravity anomaly 3) Richat—50 km diameter; associated gabbro, dolerite, and alkalic rocks —coesite reported but not since confirmed; central breccia 4) Semsiyat—5 km diameter; flattened dome; small central depression
Charlevoix Structure (Quebec)	• single crater 35 km diameter; shock features and breccias (Rondot 1971) • lies across Logan's Line fault which separates Appalachian Foldbelt from Grenville Province (St. Lawrence Valley rift)

* Papers cited are for general reference only; not all authors of specific references support a genetic relationship to tectonic features.

* Disturbance = Cryptoexplosion structure

Card *et al.* (Chapter 2, this volume) and Gupta *et al.* (Chapter 18, this volume) have shown that the Sudbury Structure is associated with one of several positive gravity anomalies that form a 340 km long curvilinear trend (inset A, Figure 21.4). The author has also provided an alternative interpretation of the gravity anomalies in the form of 2 linear trends (inset B, Figure 21.4). These trends intersect in the vicinity of the Sudbury Structure.

Examination of the Magnetic Anomaly Map (Map NL-17AM, back pocket) reveals 2, large, intense, aligned, elongate, positive magnetic anomalies that are pointed out by Card *et al.* (Chapter 2, this volume). These anomalies coincide with the gravity anomaly trend and lie north of the Grenville Front Boundary Fault. Other positive magnetic anomalies, which occur near Reservoir Lac Decelles, Quebec, about 200 km away, and east of Reservoir Gouin, Que-

bec, about 400 km away (Morley *et al.* 1968), lie north of this structural discontinuity. The location of these anomalies, parallel to and north of the Grenville Front Boundary Fault, is likely not a coincidence. It is not clear, however, whether they were the result of crustal magmatic activity before, during, or after the Grenville Orogeny, and whether the location of the Grenville Front Boundary Fault was in fact not controlled, at least in part, by pre-existing deep-seated crustal features associated with the Superior Province craton margin. Nevertheless, the Sudbury Structure anomaly is likely associated with the Sudbury Igneous Complex and deeper seated igneous bodies (Gupta *et al.*, Chapter 18, this volume) which are pre-Grenvillian. Its elongate shape is likely not due to significant deformation based on points raised in the section entitled *The Shape of the Sudbury Structure and Sudbury Igneous Complex*. The other anomalies, particularly the

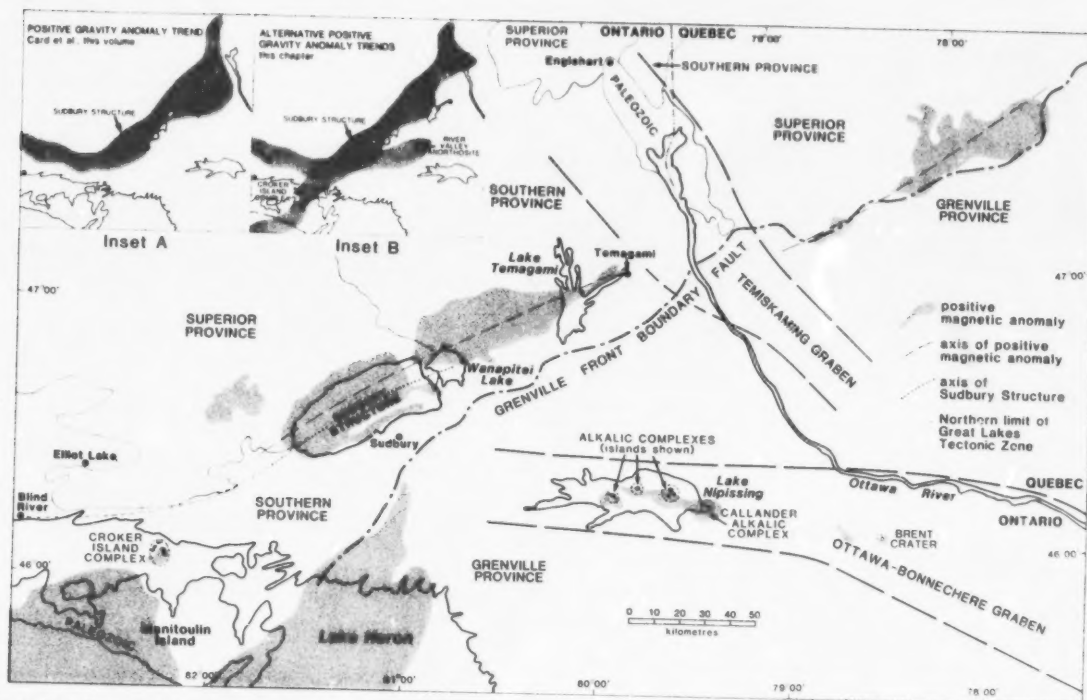


Figure 21.4. Relationship of the Sudbury Structure to major crustal features: Precambrian provinces; tectonic zones; grabens; alkalic complexes; craters; aeromagnetic and gravity anomalies.

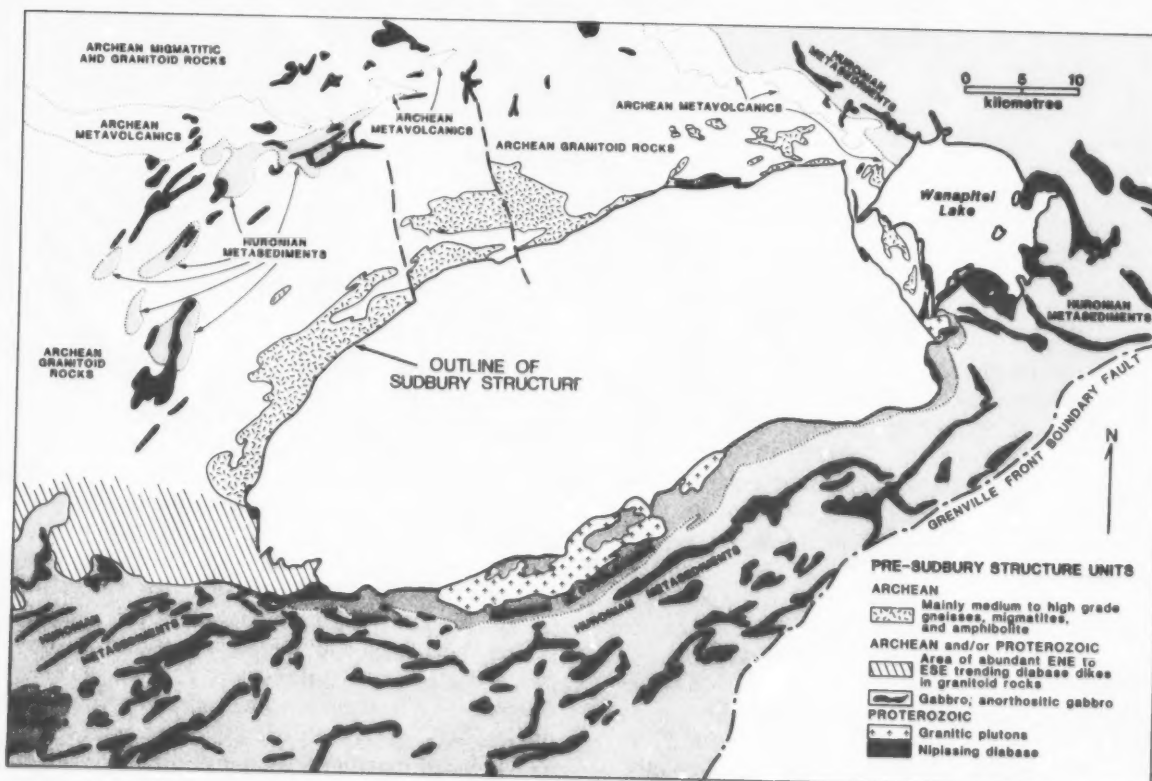


Figure 21.5. Relationship of the Sudbury Structure to specific lithologic units: gneisses and migmatites; plutons; sills and dikes; Huronian outliers.

one near Lake Temagami, indicate an impact was not required to instigate igneous activity.

The Wanapitei Structure lies within and beside the linear gravity and magnetic anomaly trends respectively; lies on the east-northeast extension of the axis of the Sudbury Structure; and appears to be conformable to the shape of the East Range (*see* point 6, section entitled The Shape of the Sudbury Structure and Sudbury Igneous Complex).

On a smaller scale, the relationships of the Sudbury Structure to surrounding units are depicted in Figure 21.5 and are as follows:

1. Medium to high-grade Archean gneisses, migmatites, and amphibolite bodies lie along much of the North Range. In Levack Township, at least, the high-grade gneisses occur close to the Sudbury Structure (Dressler, this volume). Mafic gneisses and amphibolite tend to be more abundant in the immediate Footwall than farther away (Muir 1981, 1983). Gneissic and migmatitic Footwall rocks of the East Range are locally high-grade (Burkhard O. Dressler, Geologist, Ontario Geological Survey, personal communication, 1983). The high-grade gneisses cannot have been raised from significant depths due to an impacting event (*compare with* Peredery and Morrison, Chapter 22, this volume) because they were at high levels and low temperatures at the time of emplacement of the Archean and Early Proterozoic diabase dikes, the deposition of the Huronian Supergroup, and the formation of Sudbury Breccias (Card *et al.*, Chapter 2, this volume).
2. The Great Lakes Tectonic Zone-Murray Fault Zone, a major crustal discontinuity (Sims *et al.* 1980; Sims *et al.* 1981; Zolnai *et al.* 1984) which lies south of and extends into the Sudbury Structure, has had a lengthy history of activity, which spans continuously or intermittently, a period of at least 1.2 Ga from Huronian volcanism to post-olivine-diabase-dike intrusion. It played a major role in: (a) localizing Huronian volcanic accumulations, which are represented by rift-related bimodal tholeiitic and mildly alkalic basalt and rhyolite (Card *et al.* 1977); (b) controlling the thickness of the Huronian succession, which roughly doubles in thickness across the zone; (c) controlling facies changes, which are dominantly fluvial to the north and shallow marine to the south; (d) localizing Gabbro-Anorthosite Intrusions (Figure 21.5; Card and Lumbers 1977); (e) localizing Early Proterozoic felsic plutonism (Figure 21.5) which does not occur north of this zone; and (f) localizing Proterozoic regional metamorphism and moderate to intense deformation south of its northern boundary. Sudbury Breccia is distributed farther to the west-southwest and east-northeast of the Sudbury Structure

(*compare with* Peredery and Morrison, Chapter 22, this volume), roughly parallel to the Great Lakes Tectonic Zone-Murray Fault Zone, than it is in a direction perpendicular to this tectonic zone. This suggests that the tectonic zone may have played some role in the Sudbury Events.

3. Numerous Nipissing Diabase sills occur along the South Range, which suggests that active faulting in the Great Lakes Tectonic Zone-Murray Fault Zone was likely within an extensional or rift(?) environment, and permitted access to underlying magma chambers. The lower Huronian Supergroup was deformed prior to the diabase intrusion as indicated by field relations (Card 1978). The outliers of Huronian metasedimentary rocks to the west and northwest of the Sudbury Structure are present as asymmetrical synclinal remnants that have been intruded by Nipissing Diabase sills which are locally discordant to the fold axes (Card and Innes 1981; Map 2491, back pocket), thereby establishing structural/intrusive relationships. The granitoid terrain between some of these outliers is intruded by Nipissing Diabase sills. The Superior Province between these outliers and the Sudbury Structure is virtually devoid of these sills. The outliers and sills are considered to be possibly related to a failed rift arm (D.G. Innes, Consultant, personal communication, 1981).

The above 3 points, coupled with point 4 in the section entitled The Shape of the Sudbury Structure and Sudbury Igneous Complex, strongly suggest that there is an ordered, non-fortuitous structural relationship among the locations of the Sudbury Structure, the high-grade gneisses surrounding the Sudbury Structure, the outliers, and the associated Nipissing Diabase sills, which cannot be solely attributed to a single catastrophic event at about 1.85 Ga.

Volcanic and Plutonic Rocks Associated with the Sudbury Structure

The Sudbury Structure has, in the author's view, directly related volcanic deposits occurring as the Gray and Black Members of the Onaping Formation, and indirectly related endogenic products occurring as the Basal Member and Melt Bodies (Discussion of the Onaping Formation by T.L. Muir in Chapter 7, this volume). This interpretation is based on features in the Onaping Formation (Muir and Peredery, Chapter 7, this volume) which, given established principles of geologic interpretation, and in the absence of demonstrable evidence to the contrary, clearly shows the Onaping Formation to consist of numerous, complex deposits which by structure, composition, and constituents had to have formed by multiple explosive events with a magmatic contribution. The most important

TABLE 21.2: ONAPING FORMATION—SUMMARY OF FEATURES

STRATIFICATION

- macroscopic and mesoscopic scales
- sharp contacts, abruptly gradational contacts
- paleorelief
- complex internal structures
- sorting and grading within and among units
- major and trace element trends corresponding to members and individual units

COMPONENTS

- composite fragments
- composite breccias
- welding: moderate to intense
- cored bombs, bombs
- lava flows
- homogeneous and heterogeneous glasses
- pumice
- shards: mafic and felsic
- phenocrysts: in matrix and fragments
- sulphide fragments and sulphides
- accretionary and armoured lapilli
- genetically related dikes: spherulitic and flow-banded
- shock-metamorphic features

features of the Onaping Formation are summarized in Table 21.2. If the volcanism associated with the Onaping Formation was impact-induced, the location of an impact on an area underlain by a gas-rich and sulphide mineral-rich crust adds to the list of fortuitous relationships.

The Onaping Formation displays the general features of ash-flow deposits and pyroclastic flows as given by Smith (1960a, 1960b, 1979), Ross and Smith (1961), Peterson (1970), Heiken (1979), and Sheridan (1979). These features include: vast areal distribution; large volume; cooling units; multiple ash-flows; units with relief (primary and erosional); constituents (glass, rock, and crystal fragments); degree of sorting and grading; flowage features (for example, streaks or lenses of pumice concentrations); accumulations of blocks at different levels (particularly on flow surfaces); phenocrysts and xenocrysts; zones and zonal variations (for example, welding, devitrification, vapour phase crystallization, and possible fumarolic alteration); crystallization (tridymite, alkali-feldspar); and spherulitic devitrification. Scott (1966) found distinctive and in some cases repetitious trends in variations of major oxide abundances in vertical sections of 4 major ignimbrite formations. Potentially similar aspects have been noted for the Onaping Formation (Discussion of the Onaping Formation by T.L. Muir in Chapter 7, this volume), from samples where the bulk composition of the sampled breccias is controlled by the dominant type of glass fragment present. Other papers by Dereulle (1978), Nairn and Self (1978), Walker (1980), Sigurdsson and Sparks (1981), Wright (1981), and Lipman (1984) provide examples of large-scale volcanic features, such as fragment size and type,

that are comparable to features in the Onaping Formation.

In arguments against the volcanic origin for the Onaping Formation, various authors cite: the presence of shock-metamorphic features; chemically heterogeneous fluidal glasses; a variety of glasses on a thin section scale, some of which are nepheline normative; and the similarity of the Onaping Formation to breccias which are considered by many to be impact produced (French 1970, 1972b; Dence 1972; Peredery 1972a, 1972b; Dressler 1982).

The presence of shock-metamorphic features in the Onaping Formation is unquestioned, but the uniqueness to impact is. The features must be considered in terms of: all other features of the Onaping Formation (Table 21.2); the evidence presented for endogenic shock (*see* section entitled Endogenic Shock Metamorphism); and what is found at *proven* volcanic and impact sites.

There is little doubt that chemically heterogeneous and fluidal glasses were present in the Onaping Formation. However, as to the interpretation that these features, especially on the scale of microns, cannot be found in volcanic rocks (Peredery 1972a, 1972b; Discussion of the Onaping Formation by W.V. Peredery in Chapter 7, this volume), the author cites the following objections:

1. there is no glass remaining in the Onaping Formation as it has all devitrified and/or been recrystallized
2. chemical analyses of 'glass' that has undergone greenschist facies metamorphism are unreliable indicators of original composition (Fleet 1980)
3. the various compositions for the fluidal glasses (Muir and Peredery, Chapter 7, this volume) are collectively comparable to compositions of nearly all the constituent metamorphic minerals which comprise the Onaping Formation, from albite to actinolite
4. some pure mineral compositions (for example, andesine, microcline) have nepheline normative components
5. glasses derived from incompletely mixed magmas have not been fully considered
6. the comparison with volcanic rocks is made using published analyses of fresh, less altered, volcanic glasses of Phanerozoic age
7. evidence has not been presented that clearly demonstrates a rock composed of mafic and felsic minerals may be shocked to a completely glassy state with no distinguishable mineralogical domains (for example, by colour), and maintained in that state for about 1.85 Ga even after devitrification, recrystallization, and metamorphism

The comparison of results of microprobe analyses of

the Onaping Formation should: include microprobe results from equivalently metamorphosed volcanic glasses of Middle Proterozoic age, and consider the scale of polymerization of glasses (*compare with Trichet 1969; Burnham 1982*).

Various features of volcanic glasses, which can be appropriate to the origin of glasses in the Onaping Formation, are given in Table 21.3. All these features show that a meteorite impact is not necessary to pro-

duce fused xenoliths, partly isotropic xenocrysts, partial melting of siliceous and feldspathic rocks, mixed tephra, broken crystals (phenocrysts, xenocrysts), inhomogeneous glass compositions, composite glass fragments, or multiple types of glasses on a thin section scale. In addition, partial melting of feldspathic quartzite around some intrusions in Scotland (Platten 1982) resulted in textures similar to those in arenaceous fragments in the Basal Member and Footwall Breccia of the Sudbury Structure. What is necessary

TABLE 21.3: FEATURES OF VOLCANIC GLASSES SIMILAR TO ONAPING FORMATION "GLASSES".

TOPIC	DESCRIPTION	REFERENCE
Fused Xenoliths	—trondhjemite, granodiorite, gneiss, quartzofeldspathic rocks —partly to completely fused —may have: breadcrust outlines, vesicles, variety of colour, size, shape	Maury and Bizouard 1974; Le Maitre 1974; Nairn and Self 1978; Maury <i>et al.</i> 1978; Sigurdsson and Sparks 1981; Lehtinen and Sahama 1981
Xenocrysts	—quartz and plagioclase —partly isotropic, incipient melting on fractures	Pichler and Zeil 1972
Magma Mixing	—features: inhomogeneous glass composition; wide range of composition in glass inclusions; banded pumice; mafic clots in siliceous pumice or lava —fiamme: heterogeneous composition and variety of morphology compared to matrix	Huppert <i>et al.</i> 1982 Kurchavov 1980
Heterogeneous and Multiple Glasses	—7 types of glass in deposits from one eruption: —icelandite; basalt —4 types of pumice: 1) < 0.5% phenocrysts 2) contained composite glass inclusions 3) intimately mixed basalt and rhyolite with xenocrysts and phenocrysts 4) crystal rich —partly fused xenoliths —considerable range in composition	Sigurdsson and Sparks 1981
Thin section scale	—glasses show: 1) considerable variation; mixed and unmixed from one eruption 2) inconsistent variation of alkalis 3) K ₂ O, Na ₂ O can each range by a few percent —Archean hyaloclastite—glasses with: bands, rims, spherulites, variety of colours and devitrification patterns, different mineral components (microprobe)	Sigurdsson and Sparks 1981 sample collected by N.F. Trowell; examination by author
Homogeneous Glass	—young basaltic glasses (sideromelane and palagonite): considerable variation in chemical composition within single glass grains	Bonatti 1965; Andrews 1977, Baragar <i>et al.</i> 1977
Normative Calculations	—glasses from above locations and other locations with mixed tephra: 50% of localities have some nepheline normative glasses	based on rock and/or glass chemistry given in above publications and others

* Geologist, Ontario Geological Survey

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though, for the above endogenic features, is one or more high-temperature magmas and time to develop the melting. Fused features, as described in Table 21.3 can result from thermal and/or pressure (for example, rapid release) effects. Their presence does not in itself establish whether normal thermal conduction or shock pressures took place. This applies as well to similar features in the Onaping Formation. Furthermore, the features that may be attributable to diaplectic glasses and shock melting, which likely did exist, are subject to the same possibility of being produced by endogenic shock metamorphism as are shatter cones and planar

lamellae in quartz and feldspars (*see* section entitled Endogenic Shock Metamorphism).

Favourable comparisons of the Onaping Formation to breccias at the Ries Crater draw on aspects which should be reconsidered. Various differences and similarities among Onaping Formation units, a variety of volcanic deposits, and Ries Crater breccia units are condensed and presented in Table 21.4. One must keep in mind when evaluating the comparison that: the Ries Crater is a strongly suspected, but technically unproven, impact crater; and the very sharp contact between the Bunte Breccia and ejecta suevite breccia

TABLE 21.4: COMPARISON AMONG FEATURES OF THE ONAPING FORMATION BRECCIAS^a, VARIOUS VOLCANIC DEPOSITS^b, AND RIES CRATER BRECCIAS^c.

TOPIC	ONAPING FORMATION ^a FEATURE/COMMENTS	COMPARABLE FEATURES IN VOLCANIC DEPOSITS		COMPARABLE FEATURES IN CENTRAL RIES CRATER BRECCIA ^c	
		OCCUR- RENCE ^d	COMMENTS	OCCUR- RENCE ^d	COMMENTS
Basic Units	Basal Member:	Y:P	Explosion breccia: Caldera collapse breccias	N	Bunte Breccia:
	—lies within crater structure	Y:Y	—lies within crater (and outside): lies within caldera	N	—lies outside of central crater (Megablock and Vorries Zones)
	—indirectly overlies Footwall Breccia (separated by Sudbury Igneous Complex (SIC))	Y:P to N	—Footwall rocks: overlies caldera floor volcanic deposits	N	—overlies rocks surrounding central crater rim
	—evidence of shock metamorphism	N:N	—no confirmed evidence of shock metamorphism in "normal" volcanic rocks	Y	—low shock stages generally
	—possibly up to Stage II ^e			(N)	some stage II features in some basement fragments
	—evidence of partial melting by contact and/or shock metamorphism	(Y):(Y)	—melting features are primary and volcanic (i.e. pre-explosion) or contact melting if intrusions are present, no shock melting	N	—no melting—shock or otherwise
	Melt Bodies:		Igneous Rocks:		Impact Melt:
	—intrusive igneous-textured bodies; possibly some flows	Y	—hypabyssal igneous intrusions, lava flows	N	—no intrusions, no flows
	—considered (this paper) to be a variety of, or precursor to plagioclase-rich granophyre (SIC)	Y	—related to underlying magma chamber	N	—a few small glassy bodies highly laden with fine to coarse inclusions—bodies lie outside of central crater
	Gray Member:		Ash-Flows, pyroclastic flows:		Crater Suevite ^f :
	—lies within crater structure	Y	—lies inside structure and has outflow facies deposits	Y	—lies within central crater
	—estimated to be 350 to 400 m thick		—thickness can exceed 1000 m		—about 287 m thick (scientific drillhole)
	—sharply overlies Basal Member		—sharply overlies any underlying units	N	—sharply overlies brecciated basement rocks
	—does not intrude Basal Member or Footwall Breccia			N	—basement intruded by numerous suevite and crystalline breccia dikes
	—many units defined by sharp or abruptly gradational contacts, sorting, grading, dominant type of glass	Y	—may form composite, compound cooling units or comprise any number of flows defined by similar properties	N to P	—2 main units: —lower (main) unit; 270 m thick, unbedded except for one case of a "layer" of "sorted" suevite —upper unit; 17 m thick, continuous normal graded (i.e. single) unit, sharp upper and lower contacts, overlain by reworked graded suevite units, debris flows, lake sediments (marls, clays, bituminous laminates)

TABLE 21.4: COMPARISON AMONG FEATURES OF THE ONAPING FORMATION BRECCIAS*, VARIOUS VOLCANIC DEPOSITS*, AND RIES CRATER BRECCIAS*, continued.

TOPIC	ONAPING FORMATION*	COMPARABLE FEATURES IN VOLCANIC DEPOSITS		COMPARABLE FEATURES IN CENTRAL RIES CRATER BRECCIA*	
		OCCUR- RENCE ¹	COMMENTS	OCCUR- RENCE ¹	COMMENTS
Major Features of Gray and Black Members	—consists mainly of glass, rock, and mineral fragments	Y	—consists of glass, rock, and mineral fragments	Y	—consists of glass, rock, and mineral fragments —some units in Onaping Formation appear similar to crater suevite; many though are notably different
	—most sedimentary fragments from upper Huronian cover (only units present during Sudbury Events?)		—source depends on a variety of factors	(N)	—main unit; most sedimentary fragments from lower Phanerozoic cover
	—may have one dominant type of glass or a mixed variety	Y	—commonly a single type of glass; may have up to several types	(Y)	—limited variety; ejecta suevite has greater variety
	—glass fragments (including matrix) from 25% to 75% of breccia	Y	—glass fragments can constitute over 90% of rock	N	—glass (melt) fragments (including matrix) averages 3% to 5% of breccia
	—shock-metamorphic features; possibly up to Stage IV*	N	—no confirmed evidence of shock metamorphism in "normal" volcanic rocks	Y	—shock-metamorphic features; stages 0 to IV
	Black Member: —estimated to be 1000 to 2000 m thick		—comments for ash-flows, pyroclastic flows (above) apply to thickness, units, shards	N	—no apparent equivalent in terms of shard abundance, carbon, units, overall appearance
	—similar to Gray Member properties but with many shards, different chemical composition				
	—also carbon in matrix	N	—carbon generally absent or minor (except for entrapped vegetation)	N	—no carbon in suevite
	—grades inconsistently (numerous units, poorly developed bedding) but overall into mudstones (Onwatin Formation)		—depends on local conditions	P	—partial similarity to graded unit of suevite, reworked suevite, and sediments (see above)
	—irregular contacts (between and within Gray and Black Members)	Y	—primary relief or secondary (i.e. erosion)	(N)	—possible exception noted above
	—some units dip away from basin centre (Gray Member)	Y	—dip may be away from source vent	N	—not reported
	—altered (crystallized) breccias overlying less-altered (recrystallized) breccia	P to Y	—boundaries in cooling units	N	—not reported
	—bedding—within Black Member (excludes upper part)	Y	—surge deposit or possibly airfall deposits	N	—none reported
	—upper part of Black Member	Y	—subaqueous deposits, airfall deposits	P	—upper graded unit, no beds
	—chemistry—major trend from less felsic to more mafic	Y	—within ash flows, ash-flow sheets; compositionally zoned magma chamber	N	—not reported
	—minor trends related to individual units	Y	—within ash flows, ash-flow sheets	N	—not reported
Specific Features	—welding—intense to slight; generally unwelded	Y	—all degrees of welding known	N	—none reported (some references to welding in suevite breccias in other cryptoexplosion structures appear unfounded, based on photographs)

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TABLE 21.4: COMPARISON AMONG FEATURES OF THE ONAPING FORMATION BRECCIAS^a, VARIOUS VOLCANIC DEPOSITS^b, AND RIES CRATER BRECCIAS^c, continued.

TOPIC	ONAPING FORMATION ^a FEATURE/COMMENTS	COMPARABLE FEATURES IN VOLCANIC DEPOSITS		COMPARABLE FEATURES IN CENTRAL RIES CRATER BRECCIA ^a	
		OCCUR- RENCE ^d	COMMENTS	OCCUR- RENCE ^d	COMMENTS
	—bombs, cored bombs	Y	—found locally, tend to be spatially related to vents	N	—none (in crater suevite); common in ejecta suevite
	—vesiculated basement rocks (fused)	Y	—several reported cases; partial melting	Y	—interpreted to be shock melting
	—fragments of sulphide mineralization	Y	—occurs in numerous ways (eg. cored bombs)	N	—not reported
	—phenocrysts (corroded, "fresh"; euhedral altered; see Chapter 7 on Onaping Formation)	Y	—common—ranges in different deposits from < 1% to 50% or more; mafic phenocrysts tend to become altered	N	—not reported
	—composite fragments (some complex)—found on all scales, many types, varieties; includes brecciated lithified breccias, each with glass fragments of different varieties	Y	indicates multiple stages of formation, brecciation, multiple deposits, multiple events	N to P	—some small fragments in ejecta suevite are essentially the same as the material in which they lie (simple composite) —most examples of composite fragments in the Onaping Formation have no analogue in the suevite
	—shards (mafic, felsic)	Y	—vesiculated type; thermally shattered type	N	—none reported; some glass fragments are angular
	—pumice (fits description of pumice)	Y	—common	Y	—(fits description of pumice)
	—microbreccia fragments (Sudbury Breccia)	N to P	—specific "microbreccia" not analogous?	P to Y	—reported but not clear if in crater and/or ejecta suevite (see Graup 1981)
	—accretionary lapilli; armoured lapilli	Y	—some surge deposits and some airfall deposits	P to Y	—accretionary lapilli reported but not clear if in crater and/or ejecta suevite (see Graup 1981)
	—genetically related spherulitic and flow-banded dikes	Y	—locally found	N	—none
	—multiple types of glasses	Y	—from multiple events and/or single eruptions	Y	—interpreted to be from one event; shock melting
	—mixed glass (banded, complex)	Y	—examples of partially mixed magmas	Y	—interpreted to be from incompletely mixed shocked melts

Notes:

^a Source of information: Muir and Peredery, this volume

^b Sources of information: Smith 1960a, 1960b, 1979; Ross and Smith 1961; Smith and Bailey 1968; Peterson 1970; Christiansen 1979; Heiken 1979; Sheridan 1979; Sigurdsson and Sparks 1981; Fisher and Schminke 1984

^c Sources of information: Stöffler 1971; Horn 1972; Bauberger *et al.* 1974; Füchtbauer *et al.* 1977; Jankowski 1977; Pohl *et al.* 1977; Stöffler 1977; Stöffler *et al.* 1977

^d Observations derived mostly from rocks exposed around Sudbury Basin

^e Central crater versus tectonic crater not applicable to Sudbury Structure

^f Y = yes; P = possible; N = no

^g Assumes all glass (by textural evidence) was diaplectic or shock melted which may not be the case

^h Unexposed; observations derived from scientific drilling

—crater suevite restricted to within central crater; comments in this table apply to crater suevite only except where noted

—ejecta suevite found outside of central crater: sharply overlies Bunte Breccia; average thickness is 20 m; significantly different from crater suevite in terms of volume, shape, and grain size of melt products, and volume and type of sedimentary rock fragments from units overlying basement rocks; some bedding is found outside of tectonic rim (Vorries Zone); one small lens of differently sized material found in Megablock Zone

ⁱ Footwall Breccia and Footwall rocks at Sudbury Structure: similar to crystalline breccia and brecciated basement rocks at Ries Crater, respectively; some similarities to footwall rocks of some ring-dike complexes

^j Sudbury Breccia: is similar to pseudotachylite of the Vredefort Structure; similarities to suevite and crystalline breccia dikes of the Ries Crater; may have analogues in some ring-dike complexes

^k Depends on which glasses were diaplectic, shock melted, or volcanic

^l "Breccias within breccias" in Bunte Breccia are not equivalent or comparable to composite breccias in the Gray and Black Members

(Pohl *et al.* 1977) presents a major problem because there is no known or published basis by which this relationship can be established as being a direct result of a single impact event, using either proven impact craters or man-made craters of any scale for reference.

The comparison given in Table 21.4 and a comparison with features from proven impact breccias (Shoemaker 1960; McCall 1977) shows that although the Onaping Formation is somewhat unique and unusual, it has far more in common with volcanic deposits than it does with proven and unproven impact breccias. This further serves to support the concept that the Onaping Formation is a previously unrecognized type of volcanism which involves endogenic shock metamorphism.

The presence of large-scale intrusions associated with the Sudbury Structure has been used to argue for impact-induced plutonism by French (1970, 1972a, 1972b) and Dence (1972). French (1972a) recognized there were considerable constraints involved with this and considered that requirements for such processes would be: an impact forming a crater of at least 100 km diameter; a high geothermal gradient from Nipissing Diabase intrusions or an oceanic environment; and/or a pre-existing magma chamber at depth. The first requirement is not supported by field evidence, the second is neither likely, given the age of the Nipissing Diabase, nor appropriate, given the cratonic paleoenvironment of the Sudbury Structure (Sims *et al.* 1981; Zolnai *et al.* 1984), and the third merely adds to the list of fortuitous requirements. Based on discussions presented by French and Dence, McCall (1979) concluded that "neither direct impact melting of crustal rocks nor impact-induced offloading satisfactorily explains the immense generation of magma at Sudbury." and the possible presence of a much larger magmatic intrusion at depth (Gupta *et al.*, Chapter 18, this volume) compounds the problem.

The origin of huge igneous complexes such as the Bushveld Complex (*compare with* Sharpe *et al.* 1981) and the Duluth Complex (*compare with* Pinney 1972) by conventional igneous processes is unquestioned (for example, French 1983). A comparison of various features of these intrusions reveals a wide range in both similarities and differences, such as tectonic setting, sequence of phases, rock types, layering, degree of assimilation, and mineralization; all of these features are the result of endogenic processes. McCall (1979) doubts the uniqueness of the Sudbury Igneous Complex and considers it has many similarities to the Dampier Archipelago Complex of Western Australia.

The Melt Bodies of the Onaping Formation are considered to be: bodies of "micropegmatite" (Stevenson 1963; although he did not use the term Melt

Body); and varieties of plagioclase-rich granophyre occurring as hypabyssal intrusions and possibly flows (Discussion of the Onaping Formation by T.L. Muir *in* Chapter 7, this volume). The author based his interpretation on a variety of similarities between the 2 rock types and concluded that the differences could be explained using an endogenic igneous model, calling upon aspects such as assimilation and varying cooling rates for individual bodies. The bulk composition of Melt Bodies and fluidal-textured glasses is statistically significantly different in many elements (Discussion of the Onaping Formation by T.L. Muir *in* Chapter 7, this volume) indicating the 2 rock types are not directly related genetically and/or that different degrees or types of alteration have affected them.

There are 3 types of Melt Bodies (Muir and Peredery, Chapter 7, this volume) which are the result of a variety of igneous environments. If some of the Melt Bodies are indeed flows, the volcanism may be viewed as minor coeval magmatism preceding intrusion of the main body of plagioclase-rich granophyre. The latter would form intrusive Melt Bodies. B.V. Rao (Research Student, University of Toronto, personal communication, 1983) has shown the Melt Bodies have a similar REE chemistry to the Sudbury Igneous Complex, suggesting the link between the Sudbury Igneous Complex and the Melt Bodies may be valid.

Zircons from one Melt Body and from some fluidal glass are interpreted to have shock-metamorphic features and give ages corresponding to the Levack Gneiss Complex (Krogh *et al.*, Chapter 20, this volume). The above features cannot be used to establish an impact event as they may be explained by assimilation of older crustal material, whether shocked or not. These features thus have the same constraints for interpretation as do the fused and glassy materials (*see* section on the Onaping Formation) and for the actual cause of the shock metamorphism. The degree of inheritance of zircons does distinguish these rocks from normal volcanic rocks. Nevertheless, the Onaping Formation comprises highly complex units. Further work on all types of Melt Bodies and all types of glasses, particularly the homogeneous glasses (for example, chloritized shards) is required before sufficient conclusions can be made from zircon examination regarding the origin of the Onaping Formation.

Presentations have been made for modelling the bulk composition of the Melt Bodies as combinations of various country rocks (Peredery 1972a; Discussion of the Onaping Formation by W.V. Peredery *in* Chapter 7, this volume). The modelling is limited in the variety of rock types used and involves several assumptions. The results of the modelling are significantly unrepresentative of the inclusions which are now found in the Melt Bodies and of the ratio of base-

ment rock types as presently exposed. It can be intuitively argued that any rock of intermediate composition can be modelled as a combination of any group of endogenically formed rocks of sufficiently diverse compositions, as occurs around the Sudbury Structure. The average composition of the Onaping Formation is not approximated by the Melt Bodies (Figure 7.14, Muir and Peredery, Chapter 7, this volume; *compare with* Discussion of the Onaping Formation by W.V. Peredery in Chapter 7, this volume).

Fortuitous Relationships

Numerous fortuitous relationships are required if the Sudbury Structure is due to meteorite impact. These relationships are evident in points raised throughout the section entitled Favourable Aspects for an Endogenic Origin. Every single fortuitous relationship has a probability of occurrence which is greater than zero and thus it can be argued that, given sufficient time, any particular relationship could occur. Each probability would have to be determined by taking into account: the assumed rate of impact of meteorites appropriately sized for the Sudbury and Wanapitei Structures; the ratio of abundance of a particular type of crustal/geological feature relative to the entire Earth's surface; the length of time the feature has existed and/or was active; the ratio of land area to water area; and the ratio of preserved impact craters to unpreserved craters. The probability of all the apparently fortuitous relationships occurring at one location must be a product of all the probabilities. This results in an extremely low overall probability for the Sudbury Structure relationships at an impact site. This is further compounded by the fact that, out of the only 200 or so recognized impact and cryptoexplosion craters on Earth, a very low sample population by lunar and planetary standards, many cryptoexplosion structures occurring singly or in groups of 2 or more are associated with what the author considers to be an unexplainably high frequency of significant fortuitous relationships for large impact structures (Table 21.1; McCall 1979). This suggests that not all of the cryptoexplosion structures are astroblemes.

Given our incomplete state of knowledge on geologic processes, and the unproven origin of the Sudbury Structure, the relationships between the Sudbury Structure and the regional features discussed in the section on Favourable Aspects for an Endogenic Origin, cannot be dismissed as being fortuitous without serious consideration. It is just as important for those supporting an impact origin to demonstrate that there are no genetic links between a cryptoexplosion structure and its apparent relationship as it is for those supporting an endogenetic origin to demonstrate that there are.

ENDOGENIC STRUCTURES WITH FEATURES SIMILAR TO COMPONENTS OF THE SUDBURY STRUCTURE

Diatremes, kimberlites, tuff rings, resurgent calderas, and ring-dike complexes have some features similar to various components of the Sudbury Structure and these are summarized in Tables 21.5 and 21.6, and Figures 21.6 to 21.8. All of these types of endogenic structures depend upon large volumes of gas for their explosive nature and for the fluidization of material which is emplaced as dikes, plugs, and pipes, or extruded as localized tuff rings, or as widespread ash-flows.

Important similarities of diatremes, kimberlites, tuff rings, and cones (Figure 21.6, *see* p. 467, Table 21.5) to aspects of the Sudbury Structure include explosion breccia products (*compare with* Basal Member) and the brecciated state of the country rocks (*compare with* Footwall Breccia and Footwall rocks). There are some similarities between products of deep explosions in tuff rings, tuff cones, meteorite craters, and chemical explosion craters (Heiken 1971). Important similarities of resurgent calderas and ring-dike complexes (Figures 21.7 and 21.8; Table 21.6) with aspects of the Sudbury Structure include major components such as ash-flows (*compare with* Gray and Black Members), large igneous bodies (*compare with* Sudbury Igneous Complex), effects on country rocks (*compare with* Footwall Breccia), and size and shape. For example, it would not take much ductile deformation, if appropriately oriented, of the elongate and scalloped Long Valley Caldera (Figure 21.7, *see* p. 470 to approximate the present shape of the Sudbury Structure with its embayments in the northeastern and southeastern corners. The Maroa Caldera Complex illustrates the relationship of the calderas to tectonic rifting. The Toba Caldera is much larger than the Sudbury Structure and is crudely elliptical. The Glen Coe cross-section shows major, broadly analogous features to those of the Sudbury Structure (for example, different footwall rocks on either side, ring-shaped intrusions). The Ossipee Cauldron is clearly polygonal but can be approximated to be a circular structure.

The above comparisons point out a number of factors: no single structure is completely analogous to the Sudbury Structure on any scale; a wide variation of features can be produced in endogenic structures of similar origin; no 2 endogenic structures are completely alike; and none of the above types of structures are known to be associated with shock-metamorphic features. The differences of the Sudbury Structure to any one type of volcanic/plutonic structure are likely due to: the mechanism(s) that produce shock metamorphism in cryptovolcanic structures, resulting in

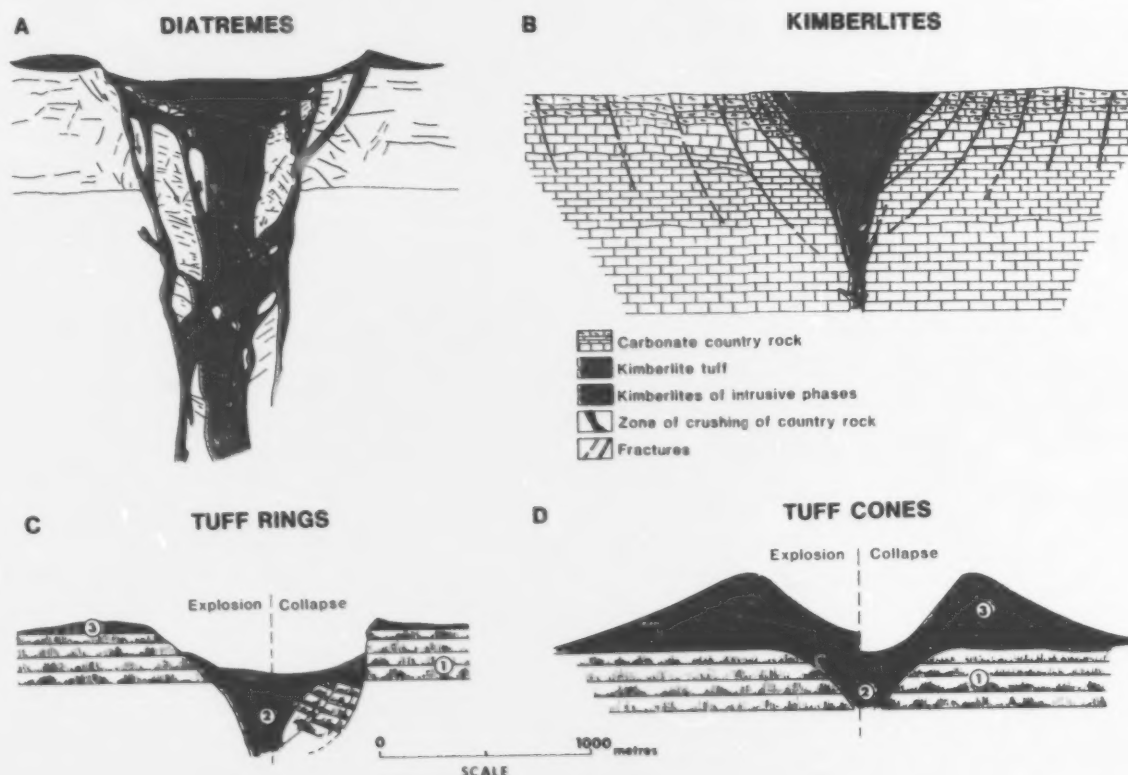


Figure 21.6. Cross-sections of specific types of volcanism involving gaseous and/or magmatic activity.

- (A) Diatreme (after Cloos 1941)
 (B) Kimberlite pipe (after Nikitin 1982)
 (C) Tuff ring (after Wohletz and Sheridan 1983)
 (D) Tuff cone (after Wohletz and Sheridan 1983)

Explanation for (C) and (D): (1) pre-existing rocks; (2) explosion breccia; (3) pyroclastic deposits.

unusual products; and the superposition of different structures, such as a caldera on an explosion crater(s), during the complex history of the Sudbury Structure.

A few comments on the morphology of the Sudbury Structure are appropriate here. The third dimension is virtually unknown except for relatively near-surface mine workings. The cross-sections of various mines in Footwall deposits (Souch, Podolsky *et al.* 1969; Naldrett, Chapter 13 this volume; Naldrett *et al.*, Chapter 11, this volume; Coats and Snajdr, Chapter 14, this volume; Davis, Chapter 16, this volume) do not appear to conform to a terraced wall configuration as outlined by Morrison (Chapter 23, this volume), except for the Levack Number 4 orebody. The scale of the terracing is inappropriate for direct comparison with appropriately sized lunar craters. The original outline of the Sudbury Structure was unlikely to have been circular as discussed in the section on Endogenic Shock Metamorphism and the establishment of its original equant polygonality is in doubt. The morphological features and processes of the Sudbury Structure (for example, slumping, terraces, embayments) as described by Morrison (Chapter 23, this

volume) do not require meteorite impact and are essentially compatible with an endogenic origin. Morrison's model does, however, require an originally circular structure.

POSSIBLE MECHANISMS FOR ENDOGENIC SHOCK METAMORPHISM

Establishing an endogenic mechanism for shock metamorphism is a more difficult task than establishing the presence of endogenic shock. Cooper (1977) compared surface bursts to deep bursts, and noted an increase in the coupling of energy to the ground with deeper explosions. This suggests that greater effects can be created from a deeper explosion of equivalent energy. Experiments by Oberbeck (1971) support this and may indicate that endogenic explosions can produce shock-metamorphic features with lower energy input than with impacts. Currie (1971a, 1971b) sug-

CHAPTER 21

TABLE 21.5: GENERAL FEATURES OF DIATREMES, KIMBERLITES, TUFF RINGS, AND TUFF CONES.

DIATREMES ¹ (see FIGURE 21.6)	KIMBERLITES ² (see FIGURE 21.6)	TUFF RINGS AND CONES ³ (see FIGURE 21.6)
—associated with considerable volumes of gas —may have no magmatic component —rapid forceful gaseous streaming from exsolution of supercritical gases —process of fluidization likely involved —range from circular to elliptical (elongate) on surface; may approach tabular shape at depth —funnel shape in upper part —controlled by fractures —may be connected to dikes at depth —can have complex internal structures —may be reactivated —contact breccia zones adjacent to wall rocks —xenoliths in diatreme fill: consist of wall-rock fragments; comprise < 1% to almost 100% —country rock blocks thrown up and outward —upward vertical displacement of material up to several km; downward displacement up to at least 1 km —fragment sizes range from minuscule to slumped blocks 100s of m long —accompanying features locally present are volcanic bombs, accretionary lapilli, composite blocks of tuff	—associated with considerable volumes of gas —generally exotic magmatic component —range from circular to elliptical (elongate) on surface; may approach tabular shape at depth —may have funnel or champagne glass shape in upper part —may be controlled by fractures —may be connected to dikes at depth —can have complex internal structures —form in 2 main stages; repeated pulses for both stages possible —stage 1) explosive—with kimberlitic tuff breccias —stage 2) intrusive with massive kimberlitic material —contact zone of breccia forms between kimberlite and country rock —matrix of contact breccia consists of fine material of same composition —associated structures: concentric and radial faults in country rock —surrounding strata may be overturned —may have dome-like fold structures around pipe with inward dipping country rock —horizontal displacement may occur between country rock beds; greatest displacement at top —maximum downward displacement of blocks may be well away from pipe —disturbed zone of downthrown blocks surrounds pipe for up to 4 times its radius —mechanical effect on country rock up to 8 times radius of pipe	—associated with considerable volumes of gas plus steam from ground and surface water —commonly magmatic (basaltic) component —generally circular; adjacent craters may intersect or amalgamate to form an elongate cavity —may be controlled by fractures —ring dikes may be present —can have complex internal structures mostly in extrusive ring/cone —from one to many explosive events of various intensities —beginning of eruptions may be rich in lithic fragments —explosion breccia features: —best developed with competent near-surface rocks (eg. sandstone) —coarse angular fragments of country rock (may be > 1 m diameter) —ash and lapilli matrix —crude stratification may develop —deeper explosions may produce crude inverted stratigraphy of fragments by rock type —overlying the explosion breccias are thinly to thickly bedded pyroclastic surge and ash-fall deposits —may have significant component of country rock fragments —proximal to vents are vesiculated tuffs, accretionary and armoured lapilli —associated structures: arcuate and concentric faults are possible

¹ References for reported details: Novikov and Slobodskoy 1978; Hawthorne 1975; McCallum *et al.* 1975; McGetchin and Ullrich 1973; Reynolds 1954

² References for reported details: Nikitin 1980, Lyons 1983

³ References for reported details: Heiken 1971; Wohletz and Sheridan 1983; Bradbury 1967

gested, citing other author's work as well, that the experimentally derived values of required peak pressures for various shock features may be lower in nature. Also of importance is the possibility of forming shock-like features without shock processes as noted by Chopin (1984) for coesite.

Several proposed mechanisms for producing endogenic shock metamorphism have been previously made and are summarized in Table 21.7. Two main principles have been proposed: (1) geometrical confinement and strain; and (2) fluid pressure either from systems involving liquid or gas, and explosion or hy-

TABLE 21.8: GENERAL FEATURES OF RESURGENT CALDERAS¹ AND RING DIKE COMPLEXES².

RESURGENT CALDERAS	RING DIKE COMPLEXES
Examples: Toba: Sumatra; Valles, Cratere, Long Valley: U.S.A.; Cerro Galan: Argentina; Fernandina: Galapagos; Aso: Japan	Examples: Glen Coe, Mull, Ardnamurchan: Scotland; Slieve Gullion: Ireland; Ossipee: U.S.A.; Sande: Norway; Liruei: Nigeria
Shape: —circular to elliptical; strongly dependent on regional structure and source geometry —commonly scalloped outlines from slumping and erosion; may be crudely polygonal	Shape: —circular to elliptical —may have scalloped outline; polygonal outline common
Size: —generally > 12 km diameter; up to at least 100 km long	Size: —about 20 km (information in referenced papers is limited)
Depth: —up to 1 km (not exclusive of caldera infill)	Depth: —up to several km?
Associated Features: —voluminous ash flows—collectively up to about 2000 km ³ —individually up to about 1000 km ³ —may have a ring fracture zone (not necessarily circular) which bounds displaced caldera mass; has steplike differential displacements —adjacent calderas may amalgamate —may have large negative gravity anomaly if not modified by later denser intrusions —some calderas have no resurgence or doming —wall slopes from vertical to angle of repose —caldera floor: littered with talus, fallback material, covered by lava plains —may be associated with mixed magmas; heterogeneous tephra —typically occur as part of a long-term sequence of endogenic events —commonly tectonically controlled —subvolcanic analogues are probably ring dike complexes	Associated Features: —subvolcanic analogue of calderas —ring dikes may consist of gabbro (including norite), granophyre, felsite —may have "intrusive agglomerates" which look like conglomerates; consist of granitic blocks in a matrix of abraded or crushed equivalents —occurs as concentric or arcuate (plan) structures —delineation of wall rock/intrusion contact may be difficult: —rocks grade from brecciated (fractured) to breccia (intense brecciation) —some shattered units and dikes in Footwall rocks can be traced because of little displacement —may have complicated relationships among brecciated rocks: eg. breccias in breccias —may be associated with magma mixing —may have sill-like intrusive breccias in down-faulted volcanic rocks —may have flinty breccias of crushed, titrated rocks (pseudotachylite?)

¹ References for data presented: Smith and Bailey 1966; Lipman 1975; McKee 1979; Francis 1983² References for data presented: Reynolds 1954, 1956; Smith and Bailey 1966; Bailey and Clough 1924; Marshall and Sparks 1984

draulic processes. Currie (1972) considered the role of volatiles to be of utmost importance and he proposed that a water-poor system with hydrogen gas created the catastrophic explosion(s) to produce shock metamorphism at the Manicouagan Structure. Schreyer (1983) considered that CO₂ was likely the predominant gas phase involved in the mechanism(s) which created shock metamorphism at the Vredefort Structure.

The variety of features among many cryptoexplosion structures, particularly those that have a relationship with linear crustal features, leaves open the possibility that more than one mechanism can produce endogenic shock metamorphism. The author considers that a likely mechanism for the Sudbury Structure involves processes akin to diatreme formation that are on a scale much larger than is the case for typical diatremes.

ENDOGENIC MODELS FOR THE SUDBURY STRUCTURE

A number of volcano-tectonic models have previously been published for the origin of the Onaping Formation and/or the Sudbury Structure; these are condensed and presented in Table 21.8. Some of the aspects raised, notably those of Speers (1957) and Stevenson (1961, 1963, 1972), are in part applicable to models that are presented in this chapter. Because there are many critical aspects of Sudbury geology still unresolved, the author proposes 2 basic endogenic models which can be considered in a spectrum of solutions. For brevity, most features common to both models have not been described twice. Model A, therefore, contains the most details. The models are presented in condensed form in Table 21.9 and as simplified cartoons in Figure 21.9. The entire history is not

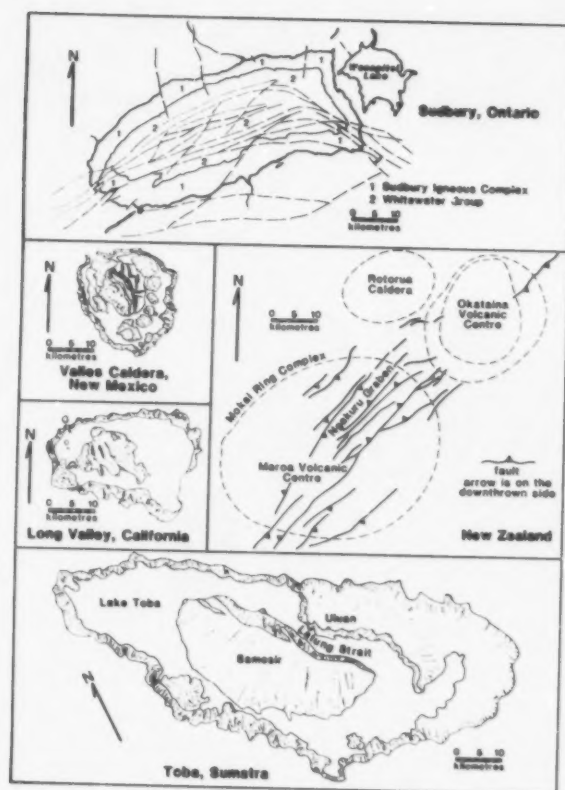


Figure 21.7 Comparison of plan view of Sudbury Structure with selected resurgent calderas: Valles, Long Valley, and Toba Calderas (after Smith and Bailey 1968); Maroa-Rotorua-Oka-taina Caldera complex (modified after Smith and Bailey 1968). All calderas drawn to same scale.

presented, but only those features deemed appropriate to the volcano-tectonic processes. The following account provides more details.

Model A

INITIAL SETTING

The setting of the Sudbury Structure is very complex and reflects numerous endogenic processes that occurred in the area over a period of at least 700 million years prior to the initiation of the Sudbury Events. The relationship of the Sudbury Structure with crustal features is given in the section entitled Structural and Geological Setting of the Sudbury Structure. It is considered possible that some of these pre-existing features played a major role in subsequent events and localization of the Sudbury Structure.

The Archean medium to high-grade gneisses along the North Range are not considered to be directly related to the Sudbury Events (*compare with* section entitled Structural and Geological Setting of the Sudbury Structure) and thus are drawn already in po-

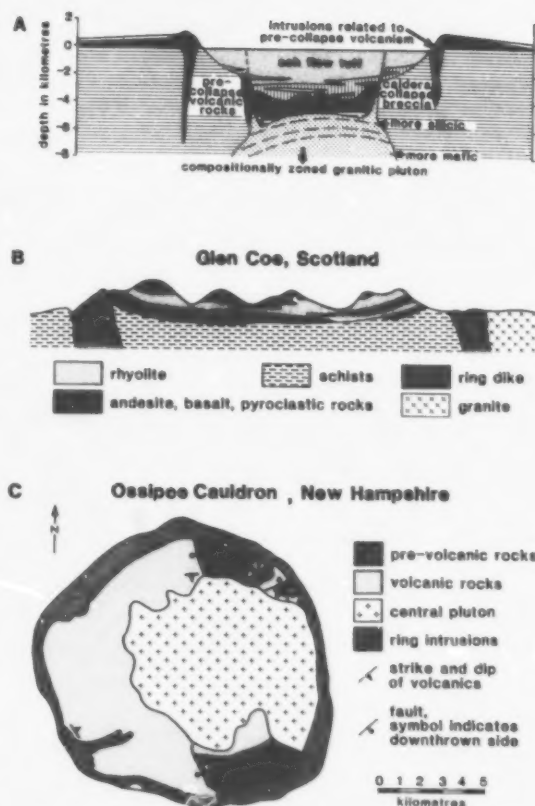


Figure 21.8. Selected examples of caldera/ring dike complexes for comparison with Sudbury Structure.

(A) Cross-section of general model of a stage in resurgent caldera after ash-flow eruptions and concurrent caldera collapse (modified after Lipman 1984).

(B) Cross-section of Glen Coe ring dike complex (after Bailey and Maufe 1916).

(C) Plan view of Ossipee Cauldron (after Kingsley 1931).

TABLE 21.7: PREVIOUSLY PROPOSED MECHANISMS FOR ENDOGENIC SHOCK METAMORPHISM.

MECHANISM	REFERENCE
Geometrical Confinement and Strain	
A) Lateral confinement of pressure through process of diapirism to produce shatter cones with orientation towards single point	Jamieson (1963) Nicolaysen (1972)
B) Sudden release of high hydraulic pressure by arching, fracturing, collapse: produces shatter cones and chaotic breccias	Goguel (1963)
Fluid Pressures	
C) Geometrical confinement, tectonic overpressure, and gas explosion	Currie (1972)
D) High pressure hydrothermal fluids produce breccia pipes with shock metamorphism	Godwin (1973)
E) High hydraulic pressures from confinement of fluids in horizontal fault planes	Kopf (1982)
F) Diatreme—kimberlite intrusion mechanisms	Reidel <i>et al.</i> (1982)

TABLE 21.8: PREVIOUS VOLCANIC MODELS FOR THE SUDBURY STRUCTURE.

REFERENCE	MAJOR OBSERVATIONS/CONCLUSIONS	COMMENT (THIS CHAPTER)
Bell (1883)	—interpreted the Onaping Formation to be a result of volcanism which entailed violent activity on a large scale	
Coleman (1905)	—interpreted the Onaping Formation to be deposited entirely in a subaqueous environment	
Collins (1936)	—suggested that the Sudbury Igneous Complex was genetically related to the Onaping Formation	—important interpretation
Burrows and Rickaby (1930)	—considered that continuous explosive activity took place on an enormous scale —most of Onaping Formation was subaerial and more extensive than its present distribution indicates —large fissures or row of vents were parallel to the long axis of the basin —Huronian volcanic rocks south of the Sudbury Structure were coeval with the tuff, coarse breccias, and spherulitic and pillowed lavas of the Onaping Formation —carbon in the Onaping Formation (mostly Black Member) considered to have resulted from reduction of CO ₂ and/or CO —compared average chemical composition of Sudbury Igneous Complex (Coleman, Moore and Walker 1929) to average composition of Onaping Formation: concluded they were similar except for Al ₂ O ₃	—now known not to be coeval —pillows not since confirmed —cf. Williams (1957)
Moore (1930)	—mentioned violent volcanic eruptions to form Onaping Formation —noted Wanapitei Lake resembled a crater in many ways	—Wanapitei (cryptoexplosion) Structure
Cooke (1946)	—noted bedding (2 to 50 feet thick) in Onaping Formation with planes straight and parallel to each other	—first description of well defined units
Thomson (1957)	—much of lower part of Onaping considered to be rhyolite and rhyolite breccia with feeder dikes —fissures for Onaping Formation located in a ring at or near the present upper granophyre contact	—Basal Member—essentially quartz arenite, arkose and granitoid rocks —specifically: one "rhyolite plug and feeder dike" is a huge block of quartz arenite and slabs of quartz arenite, respectively
Williams (1957)	—interpreted some rocks of the Stobie Formation to be coeval basalts erupted from fissures outside of the ring of fissures —lower part of Onaping Formation consists of Pelean Domes —remainder of Onaping Formation consists of rapidly deposited, accumulated glowing avalanche deposits which broke through and partly destroyed the Pelean Domes —most common type of fragment in glowing avalanche deposits is rhyolite which when comminuted supplied rounded magmatically corroded quartz xenocrysts —ejecta did not fall as showers (little evidence of stratification); the minor stratification does not have airfall characteristics —avalanches followed by sedimentation to form Onwatin and Chelmsford Formations in basin, and upper Stobie, McKim, and Bruce Formations outside basin —carbon in Onaping Formation is likely organic; percolated down by ground water movement —emptying of 1250 km ³ caused further subsidence of Sudbury Basin to produce a "volcano-tectonic sink"; could not say what caused the initial depression —Sudbury Igneous Complex consists of a number of injections (norite, then granophyre) controlled by a fissure zone which marked the margins of a pre-existing cauldron, not an actively sinking one	—Stobie Formation much older —Basal Member—not Pelean Domes —Gray and Black Members —few rhyolite fragments but there are some —magmatically corroded quartz crystals still interpreted to be phenocrysts —important interpretation; cf. Stevenson (1961) —sediments outside of basin are much older (Huronian) —cf. Burrows and Rickaby (1930) —important interpretation

sition in the model diagrams. However, the spatial relationship suggests indirectly related, pre-Sudbury Events tectonic forces may have resulted in their present position. The mechanism for raising the high-grade

gneisses up from depths of the order of 20 km is problematic, as is the case in some other gneiss terrains. Possible mechanisms include major faulting (for example, horsts or thrusts) or diapirism, possibly form-

TABLE 21.8: PREVIOUS VOLCANIC MODELS FOR THE SUDBURY STRUCTURE, Continued.

REFERENCE	MAJOR OBSERVATIONS/CONCLUSIONS	COMMENT (THIS CHAPTER)
Thomson and Williams (1959)	—combined conclusions of Thomson (1957) and Williams (1957) —suggested the Sudbury Igneous Complex was not a lopolith because of relationships of Onaping Formation to coeval Stobie and McKim Formation	—not coeval
Speers (1957)	—related Onaping Formation, Sudbury Breccia and Sudbury Structure in one model —proposed crustal forces formed a domal structure (affecting the Huronian and older rocks) which controlled the emplacement of a large magma body beneath the dome —large amounts of volcanic gases continuously issued, with extreme violence, over a short time, from the central part of the dome and accompanied material which formed the Onaping Formation —fluctuating pressures caused tension fractures to open and close thereby crushing any loose wallrock material —collapse after volcanism ceased led to further crushing —collapse produced Sudbury Basin —Sudbury Breccias considered to be water saturated and behaved in part as a fluid (see also Fairbairn and Robson 1942) —Sudbury Igneous Complex intruded along caldera walls —Onwatin and Chelmsford Formations formed from basin infilling —considered Onaping Formation to be much younger than rocks outside of Sudbury Basin	—first 'complete' model for Sudbury structure —Sudbury Breccia
Stevenson (1961)	—recognized quartzite breccia at base of Onaping Formation in South Range —recognized "zones" of breccia in Onaping Formation from 30 to 300 m thick which were defined by mappable "size-distributions" of fragments and had "considerable" strike continuity —interpreted Onaping Formation to consist of normal airborne fallout locally with some waterborne sediments	—important observation; Basal Member —important observation —Williams (1957)
Dietz (1964)	—invoked meteorite impact to initiate volcanic and impact melt rocks; considered Onaping Formation welded tuff	—most of Onaping Formation is not welded
Thomson (1969)	—combined meteorite theory with volcanic theory —impact considered to induce magmatic activity and volcanism in accord with suggestions of Thomson (1957), Thomson and Williams (1959) —concluded Sudbury Breccias were not feeder dikes for Onaping Formation	
Stevenson (1972)	—showed examples of intense welding in Onaping Formation —used distribution and degree of welding to interpret the Onaping Formation as consisting of several ash-flow units to form a sheet —the units erupted rapidly from fissures to form a single cooling unit —included Sudbury among the many examples where fissures to ash-flow sheets have not been located	—important interpretation of presence of ash-flows
Muir (1983)*	—considered that a possible impact may have induced volcanism but that the Onaping Formation was largely volcanic —noted composite fragments of a wide variety throughout the Gray and Black Members and concluded that they formed from multiple events —reported fragments of sulphide mineralization in the Onaping Formation and inferred pre-existing or coeval sulphide bodies	
Muir (1982)*	—noted numerous sharp contacts between numerous units, and planar bedding; major contact between Gray and Black Members—reiterated multiple event interpretation —noted some units dip away from the centre of the basin and inferred that the structure of the Onaping Formation is more complex than generally considered	

*Field work for Muir (1983) was done in 1981 and written in early 1982; field work for Muir (1982) was done in 1982 and written in late 1982.

ing a pre-Sudbury Structure dome, long eroded by the time of the Sudbury Events. The non-conformability of the gneisses to the outline of the Sudbury Igneous Complex does not preclude the existence of such a dome because the explosion craters of the Sudbury Events do not require conformability to the Footwall macrostructures. More field work is needed in this regard. Gneisses do occur elsewhere in the area (for example, north of the Benny Greenstone Belt, and north

of the map area), but are not associated spatially or by metamorphic grade to any major superposed structure.

Most folding of the South Range Footwall predated the Sudbury Events (see section entitled The Shape of the Sudbury Structure and Sudbury Igneous Complex) and can be spatially related to deformation and metamorphism throughout the Great Lakes Tectonic Zone-Murray Fault Zone of the Southern Province, not just south of the Sudbury Structure (Sims *et*

TABLE 21.9: OUTLINE OF TWO ENDOGENIC MODELS FOR THE SUDBURY STRUCTURE.

MODEL A	MODEL B
INITIAL SETTING —area with complex history of plutonism, volcanism, metamorphism, deformation —deep crustal faulting within Murray Fault Zone (MFZ) —possibly located over mantle hot spot —site of Sudbury Structure is spatially related to Archean high-grade gneisses, Early Proterozoic granitoids, anorthositic gabbros, Nipissing Diabase, Huronian metavolcanic and metasedimentary rocks —high-grade gneisses and Huronian outliers already in place —considerable folding of Huronian Supergroup in MFZ	INITIAL SETTING —similar to Model A except Nipissing Diabase intrusions may be direct antecedents of the large sub-Sudbury Structure intrusion considered at least partly in place at this point —crustal melting is initiated around the large igneous bodies
SUDBURY EVENTS EARLIER STAGES —fault penetrates lower crust, possibly mantle —diatreme-like process initiated at a number of places along fracture —hot, high-pressure gas or liquified gas rises (possibly CO₂, CO), tearing off wall rock fragments; becomes fluidized mass —partial melting of fragments may occur —explosions occur near surface when lithostatic pressure is rapidly and greatly exceeded by fluidized mass; behaves as buried explosions —effect of explosion may have been increased by a cap of Huronian rocks —explosion craters form from closely spaced diatremes on fault plane —craters amalgamate to form elongate cavity; crater wall slumping along preferred fracture systems modifies cavity somewhat —shock-metamorphic features produced; possibly from more than one explosion —Sudbury Breccia—produced from mechanical crushing, some fusion —forms irregularly shaped bodies, pipe-like bodies, linear bodies —Sudbury Igneous Complex—location controlled partly by pre-existing fractures and partly by explosion-created fractures —Footwall Breccia—crater wall breccias; mostly autochthonous breccia —proto-Basal Member (ie. before intrusion of Sudbury Igneous Complex—explosion breccia and slumped material from upper walls; mostly allochthonous breccia)	SUDBURY EVENTS EARLIER STAGES —volcanism was initiated—building up an unknown number of edifices —variety of magmas—gives variety of glasses and products —variety of eruptions—lapilli-tuff, tuff, welded tuffs, flows —material formed pre-Onaping deposits
LATER STAGES —Gray Member magmas of crustal or deep lithospheric derivation erupt to form tuff rings, pyroclastic flows, and ash-flows by violent gaseous eruptions —parts of succeeding deposits are re-brecciated by successive eruptions —composite fragments and composite breccias (initial deposits) incorporated with new material and country rock fragments —occasional quiescent eruptions form lava flows; fluidal-textured bodies, some Melt Bodies —part of tuff rings forming inside crater would have outward dipping beds as in part of the Gray Member —may have had subsidence of the structure —interval of unknown duration—contact between Gray and Black Members —Black Member—eruption of more mafic material, possibly triggered by intrusion of SIC or sub-Sudbury Structure igneous body or both —violent eruptions form ash-flow-like deposits and incorporate parts of brecciated Gray Member units —deposits noted for mafic shards, especially in early stages to form shard-rich horizon —possibly some surge deposits to produce bedding	LATER STAGES —violent eruptions through ring-like fissures from the pre-Onaping volcanic system; shock metamorphic features were produced along fissures —gas release related to instability in the large sub-SS intrusion caused widespread but locally concentrated Sudbury Breccias —triggered possibly by injection of hot magma into compositionally zoned chamber producing flashing and rollover —Gray Member—Plinian eruptions start the deposition of new volcanism as ash-flow units —deposits incorporate much brecciated material from pre-Onaping volcanic rocks—gives composite fragments, sulphide fragments etc. —massive caldera-like collapse possibly during early parts of eruptions —Basal Member—caldera collapse breccias along country rock walls with fragmentation similar to that in ring dike complexes —eruptions continue to deposit Gray Member units —interval of unknown duration—contact between Gray and Black Members —infusion of more mafic magma possibly from large sub-

CHAPTER 21

TABLE 21.9: OUTLINE OF TWO ENDOGENIC MODELS FOR THE SUDBURY STRUCTURE, Continued.

MODEL A	MODEL B
—may have invoked more than one type of magma including alkalic varieties —may have had subsidence of the structure —genetically related dikes intrude Gray and Black Members (flow-banded, spherulitic) —timing of intrusion of SIC not fully known —early phases of plagioclase-rich granophyre intruded proto-Basal and Gray Members (possibly Black Member), to form other Melt Bodies —matrix of proto-Basal Member converted by partial melting, recrystallization to form present Basal Member —probably indicates intrusion of SIC was concomitant or shortly to come	- SS intrusion causes more instability —Black Member—magma chamber now erupts more mafic material—deposits are initially rich in mafic shards —Plinian eruptions form more ash-flows; includes some brecciated Gray Member units and earlier volcanic deposits —genetically related spherulitic and flow-banded dikes intrude Gray and Black Members
POST-SUDBURY EVENTS —volcanism waned; infilling of basin dominated by sedimentation —Onwatin Formation—fine volcanic detritus as silt and mud washed in gradually filling up internal lake; —Vermilion Member formed during early stages of basin sedimentation —carbonates and volcanogenic-style sulphides deposited (Zn-Pb-Au-Ag-Au) —carbon formed: reduction of CO, CO₂(?); biogenic material (?) —basin subsidence and/or surrounding uplift—may reflect magma activity related to SIC and/or larger sub-SS igneous body —Chelmsford Formation—turbidites formed from material slumping off basin sides; wackes and silts —Onaping, Onwatin, and possibly Chelmsford Formations locally intruded by gabbroic dikes —timing of many aspects of large sub-SS igneous body and SIC not known —SIC—multi-phase intrusion penecontemporaneous with some deformation —significant crustal contamination through assimilation of breccias —main intrusion(s) separate Footwall Breccia and proto-Basal Member to create distinct Basal Member intruded and infiltrated by granophyres and their fluids —sublayer and orebodies likely post-norite and multi-phase —may be related directly to large sub-SS intrusion/layered (?) intrusion —subsequent deformation—mostly within Murray Fault Zone	POST-SUDBURY EVENTS —similar to Model A —uncertainty over timing of plutonic activity (SIC; sub-SS intrusion) precludes refinement of events as with Model A

al. 1981). Later crustal compression of the Huronian units against the Sudbury Igneous Complex, which acted partly as a buttressing force, caused overturning of the units along parts of the South Range Footwall. This can explain the so-called overturned collar (Dietz 1964) without an impact, and accounts for the field relationships, particularly the present Sudbury Breccia orientations.

SUDBURY EVENTS

Earlier Stages

The Sudbury Structure may be directly associated with mantle perturbations, a hot spot, a strong fracture control system, or any combination of these. Faulting

within the Great Lakes Tectonic Zone-Murray Fault Zone penetrated the crust, possibly even the mantle. Diatreme-like activity, involving gas or liquified gas, utilized the lower pressure gradient at a number of places along the fracture for access to the surface. As pressure decreased, the mass of fluid accelerated ripping off fragments of wall rocks and gradually enlarging a channel. At shallower depths, the fluidized material was still largely confined by the fracture, was under very high pressure and temperature, and behaved as a rapidly moving mass with substantial kinetic energy. The wall rocks were suddenly exposed to the entrained heat and pressure of the fluidized mass which put the rocks under intense stress. Heat and subsequent release of pressure could completely or partly melt some of the wall rock fragments. Near the sur-

face, the pressure exerted by the rapidly moving fluidized mass suddenly exceeded the lithostatic pressure, and immense energy was rapidly released behaving as a series of buried explosions to form craters that amalgamated along the fracture system (Figure 21.9, A1). The cap of Huronian metasedimentary rocks may have enhanced overpressures during the explosive process (see explosion breccias, Table 21.5). Subsequent pulses could have created more explosions. Shock-metamorphic features are postulated to have formed during one or more of these explosions.

In support of the model, the following points can be made. The Murray Fault Zone has crustal dimensions (Zolnai *et al.* 1984). Wernicke (1981) has advocated the possibility of brittle mantle failure. Wyllie and Huang (1976) suggested that at depths of about 80 km, a considerable change in the solubility of CO₂ occurs, and free CO₂ could exist under conditions of unusually high temperature. A fracture through the crust to this 80 km depth would create sudden instability for CO₂ 'stored' as carbonate (Wyllie and Huang 1976) or for gases or liquids (see also Currie 1972, regarding the role of H₂); CO has been suggested as an alternative fluid phase because of the high temperatures and pressures at deep levels (A.D. Mutch, consulting geologist, personal communication, 1983).

It cannot be demonstrated at this point that the peak pressures required to produce shock metamorphism of the sort found in the Sudbury Structure (at least a few hundred kb, as extrapolated from experimental data based on smaller scale examples) can be produced by such a mechanism. The claim by various authors (for example, French 1968; Discussion of the Onaping Formation by W.V. Peredery in Chapter 7, this volume) that the *near-surface* crust cannot sustain pressures due to *normal* volcanic processes which could produce shock metamorphism are likely correct, but are not contrary to the proposals in this model.

Similar processes for the genesis of diatremes have been described (McGetchin 1968; McGetchin and Ullrich 1973) and involve fluidization (Reynolds 1954). The melting of wall rock fragments during fluidization (Reynolds 1956) could explain some of the varieties of once molten and semi-molten (that is, plastic) country rock fragments of varying composition in the Onaping Formation.

Man-made and volcanic explosion craters have some features similar to impact craters (Roberts 1968; Oberbeck 1971; Wohletz and Sheridan 1983). Lyons (1983) showed that some kimberlites have upper crater walls with inward slopes as little as 10° to 15° (compare with Morrison, Chapter 23, this volume). Differences in features among these crater types are unlikely to be delineated in the Sudbury Structure at present. Diatremes, kimberlites, tuff rings and cones, and maars are locally associated with crustal-scale

features such as with the Ubehebe explosion crater (Wohletz and Sheridan 1983), Zuni Salt Lake maar (Bradbury 1967), and the lunar Hyginus Crater and Rille (Cortright 1968).

Closely spaced explosions along a fracture can produce adjacent craters which amalgamate (Wohletz and Sheridan 1983). Slumping of the crater walls would modify such an elongate depression to some extent. Evidence for fracture control of the shape of the Sudbury Structure has been described in this chapter.

Sudbury Breccia represents material blown into fractures during the rising of the fluidized mass, the explosion(s), and readjustments in the surrounding crust. Most of this material is derived from mechanical crushing with local fusion, consistent with the model of Speers (1957). The distribution of some breccia bodies was locally controlled by pre-existing fractures and rock units. Small-scale or aborted diatremes would form isolated, pipe-like or linear fracture-controlled bodies of Sudbury Breccia locally found well away from the Sudbury Structure (for example, Lake Temagami area). The different types of Sudbury Breccia (Dressler, Chapter 6, this volume) reflect different conditions at various distances from the "source" of the explosions. Locally, dikelets of one type of Sudbury Breccia may intersect other dikelets of the same type (Muir 1983). Age relationships among all types are not established.

The explosion craters would have brecciated walls represented by the essentially autochthonous megabreccia and Footwall Breccias which show shock-metamorphic features (compare with Dressler, Chapter 6, this volume). Slumping of upper crater wall and crater rim material, involving mostly shocked granitoid rocks and Huronian metasedimentary rocks in the North and South Ranges, respectively, would deposit an allochthonous breccia to form a proto-Basal Member for the Onaping Formation. Highly deformed quartz arenite fragments found locally in the Basal Member and Sudbury Breccia support the existence of pre-Sudbury Events regional deformation in some Huronian units.

Later Stages

The Gray Member of the Onaping Formation was formed from subsequent gaseous emissions coupled with magmas of either crustal or deep lithospheric derivation which used the same channels as the fluidized mass. The composite fragments in the Gray Member and the amount of finely shattered and comminuted glass fragments are best explained by these gas-rich eruptions which may have produced tuff rings within the crater(s) (Figure 21.9, A2). Occasional relatively quiescent lava eruptions would result in isolated flows presently represented by some fluidal bodies and possibly some Melt Bodies.

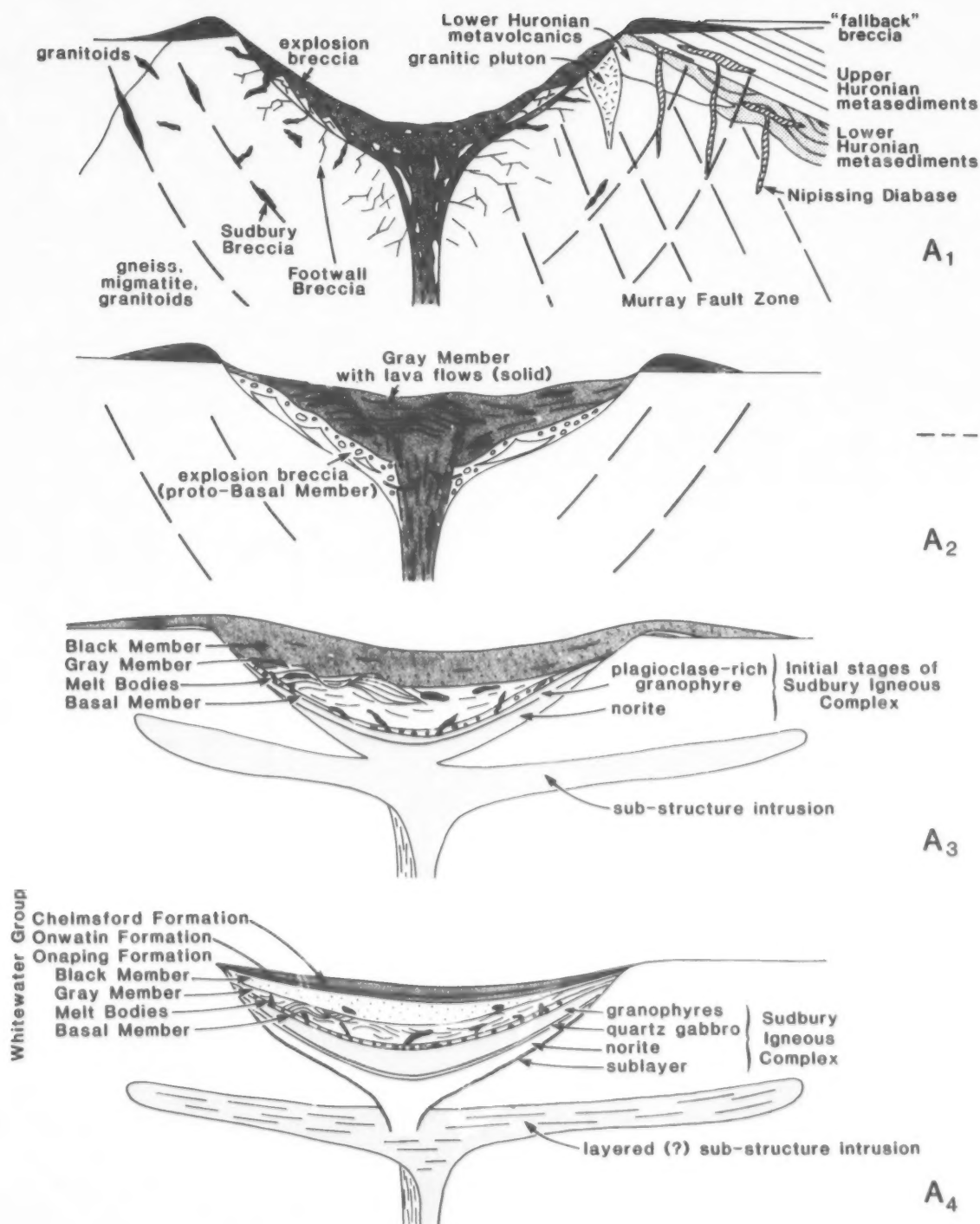


Figure 21.9. Two proposed endogenic models for the Sudbury Structure, to be considered in a spectrum of solutions.

Model A: Sudbury Events; earlier stages (A₁); later stages (A₂, A₃). Post-Sudbury Events (A₄).

Model B: Sudbury Events; earlier stages (B₁); later stages (B₂, B₃). Post-Sudbury Events (B₄).

Possible variations in each model sequence suggested by arrows from B₁ to A₁ and from A₂ to B₂.

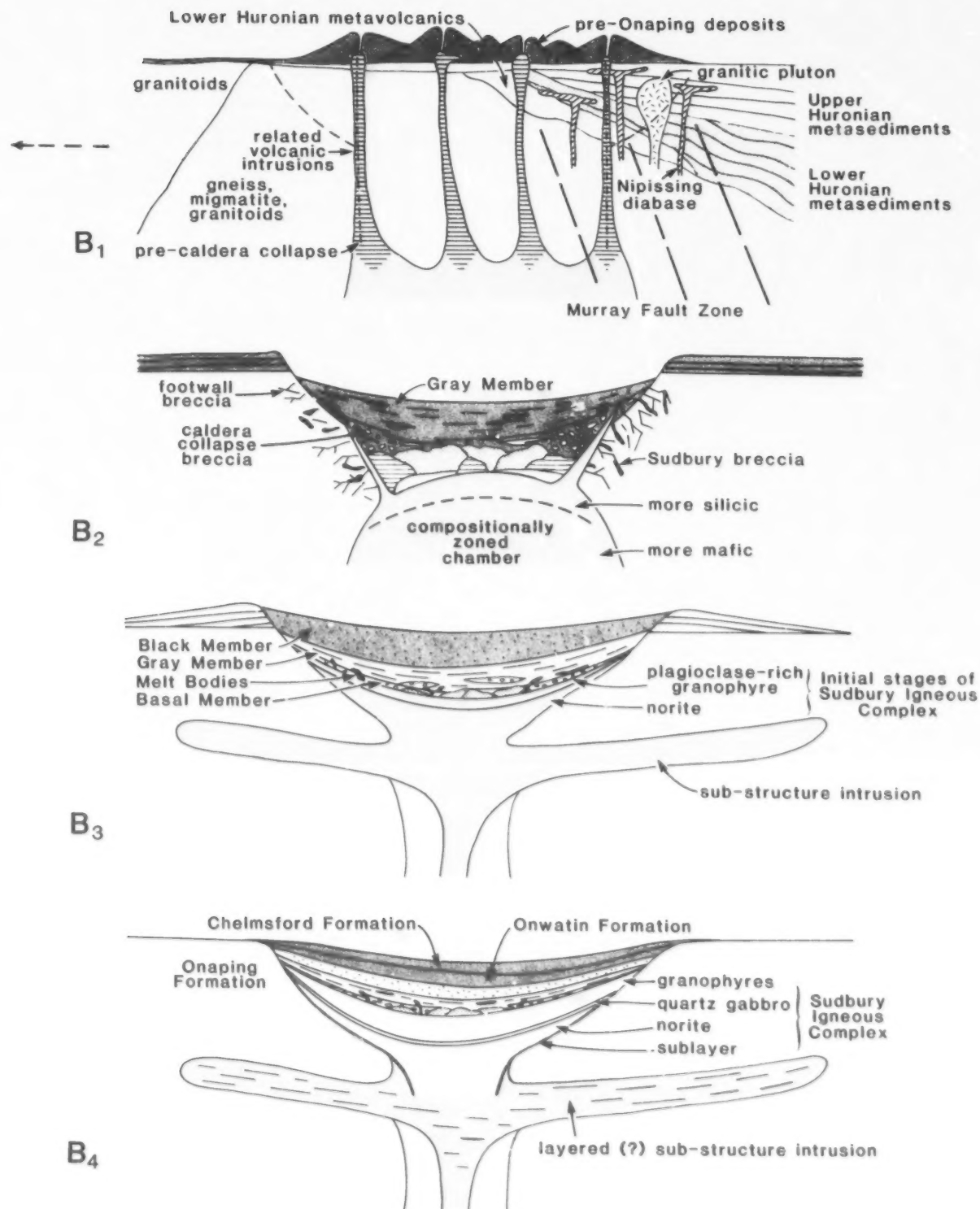


Figure 21.9. Two proposed endogenic models for the Sudbury Structure, to be considered in a spectrum of solutions.

Model A: Sudbury Events; earlier stages (A1); later stages (A2, A3). Post-Sudbury Events (A4).

Model B: Sudbury Events; earlier stages (B1); later stages (B2, B3). Post-Sudbury Events (B4).

Possible variations in each model sequence suggested by arrows from B1 to A1 and from A2 to B2.

Repeated violent gaseous eruptions would explain: the incorporation of re-brecciated tephra, tuff ring material, and country rocks; the incorporation of previously altered glass in some units; and the smaller units which have characteristics of pyroclastic flows. Tuff cones and/or rings forming inside the crater during the initial eruptions could explain the outward dip of some Gray Member units. Lengthier eruptions could form ash-flow deposits to form part of the Gray Member. The lack of unwelded glass fragments mixed in with the fluidal-textured bodies and flow-like Melt Bodies supports relatively quiescent interludes with little or no airfall (*compare with* impact fallback breccias; Peredery and Morrison, Chapter 22, this volume). The phenocryst-poor and apparently primary-zircon-free magmas may be explained by rapid rising and eruption of very hot (superheated?) deep-seated magma, which had a component derived from partly to completely melted crustal material (for example, gneiss).

An interval of unknown duration is represented by the locally sharp contact between the Gray and Black Members. This was followed by explosive eruptions of magma generally of more mafic composition which deposited ash-flows and pyroclastic flows as Black Member units (Figure 21.9, A3). Local conditions would control whether the contact between the 2 members was sharp or gradational. The Black Member is largely characterized by the presence of mafic shards especially within the layer rich in mafic shards, at the base of the member. Surge deposits could account for planar bedded units in the Black Member.

Variable intensity of eruptions combined previously existing lithic fragments with newly formed ones, and re-brecciated some of the pre-existing units to form composite blocks. As with the eruptions of the Gray Member material, the Black Member may have been formed from more than one type of magma, including incompletely mixed magmas and subordinate amounts of alkalic magma based on some alkali-rich glass fragments. Possible collapse due to magma evacuation and release of gas pressure may have modified the initial crater structure morphology to some degree.

Stevenson (1972) proposed that multiple ash-flow units formed a single cooling unit. More than one cooling unit may be present, based on the different degrees of recrystallization in the stratigraphic section. Major cooling units are likely represented by the Gray and Black Members.

The more mafic magma of the Black Member may reflect intrusion of a large, igneous body such as is proposed to lie below the Sudbury Structure (Gupta *et al.*, Chapter 18, this volume). The age of this large intrusion is unknown with respect to the Sudbury Structure, the Sudbury Igneous Complex, and the Onaping Formation.

The Gray and Black Members overall consist of relatively notable amounts of quartz arenite, arkose, and conglomeratic quartz arenite fragments which appear to be derived from the upper Huronian Supergroup. There is a conspicuously small proportion of lower Huronian fragments such as wackes, conglomerates, calcareous rocks, and volcanic rocks, as well as Nipissing Diabase that has intruded these units. This suggests that only the upper Huronian units were present at the time of the Sudbury Events. This could be explained by a topographical high in the Sudbury area during Huronian deposition, although there is some evidence to the contrary (Long 1978). The cause of this possible high may have been related to diapirism and/or faulting (horsts).

During and after the deposition of the Gray Member and possibly the Black Member, the plagioclase-rich granophyre magma, or its precursor phases was intruded into the Basal and Gray Members at various stages to form Melt Bodies. Locally, the material may have formed flows. Different characteristics of the Melt Bodies reflect differences in their level of intrusion within the Onaping Formation, the size of an individual Melt Body, the initial temperature of the magma and contact rocks, the rate of cooling and crystallization, the degree of assimilation, and the proximity to later intrusions of the granophyres.

Fluidal-textured fragments and fluidal bodies have a composition somewhat different from the Melt Bodies, but not to the degree that one could rule out concomitant igneous activity. It is possible that some of the Melt Bodies in the Black Member are actually large blocks of older, brecciated Melt Bodies. Spherulitic and flow-banded dikes, which are genetically related to the magmas, based on their physical and chemical characteristics, intruded the Gray and Black Members.

The plagioclase-rich granophyre, its pre-cursors, and the normal granophyre all affected the proto-Basal Member, particularly its matrix. Recrystallization, metasomatism, and partial melting occurred and resulted in the present form of the Basal Member matrix and fragments (Discussion of the Onaping Formation by T.L. Muir in Chapter 7, this volume).

POST-SUDBURY EVENTS

Intermittant and waning volcanism produced increasingly finer material containing fewer lithic fragments and the disrupted bedding in the upper part of the Black Member. The decrease in rate of effusion allowed sedimentation to become the dominant intrabasin process. Evidence for the subaqueous deposition of the entire Black Member as opposed to the Gray Member is doubtful (*compare with* French 1970; Peredery 1972b) because of a lack of contrasting depositional

features between the 2 members. Fine tuffaceous material, washed into the crater/basin by internally draining water, began to fill the basin with muds and silts to form the Onwatin Formation (Figure 21.9, A4). Active eruptions gave way to local hydrothermal processes which formed volcanogenic-style Zn-Pb-Cu-Ag-Au deposits presently represented by sulphide deposits in bedded carbonate-chert-bearing rocks which form the Vermilion Member of the Onwatin Formation (Rousell, Chapter 8, this volume). Mineralization within the Whitewater Group as a whole can be explained in the context of volcanic processes (*compare with* Rousell, Chapter 8, this volume).

Extra-basin uplift and/or intra-basin subsidence, possibly due to magma withdrawal, created conditions leading to erosion of largely granitoid and Huronian metasedimentary terrains. Eroded material built up and collapsed off the flanks of the basin, depositing turbidites which comprise the Chelmsford Formation. Evidence from paleocurrent data (Cantin and Walker 1972; Rousell 1972) shows the basin was elongate during this deposition, with flow toward the southwest. Cantin and Walker discussed the possibility that the provenance of much of the material for the turbidites was at the northeastern end of the basin.

Burrows and Rickaby (1930) considered the carbon in the Whitewater Group to have resulted from reduction of CO₂ or CO. The carbon may have resulted from reduction of mantle-derived CO as given in the equation $2\text{CO} = \text{C} + \text{CO}_2$ (A.D. Mutch, consulting geologist, personal communication, 1984). Mutch also suggested that fixing of this volcanogenic CO₂ during degassing of the system might explain the Vermilion Member carbonates. Some or all of the carbon in the Whitewater Group may have been biogenic (Williams 1957; Thomson 1960) related to a stagnant, anoxygic environment (Rousell, Chapter 8, this volume). Any model for the carbon must explain the fact that the carbon transgresses the Gray Member/Black Member contact of the Onaping Formation (Muir and Peredery, Chapter 7, this volume). Further research is needed to resolve the origin of the carbon.

The multiphase, cryptically layered Sudbury Igneous Complex presents numerous problems regarding many aspects of its history including its temporal relationship to the formations of the Whitewater Group. Card *et al.* (Chapter 2, this volume) and Morris (Chapter 19, this volume) consider the Sudbury Igneous Complex to be penecontemporaneous with one of the orogenic events of the Southern Province. Naldrett and Hewins (Chapter 10, this volume) and Naldrett *et al.* (Chapter 11, this volume) show that large-scale crustal contamination of the Sudbury Igneous Complex magmas has taken place. This is consistent with the presence of significant volumes of brecciated material within the initial explosion craters, and intrusion into and through the neck and channelway formed

during the initial diatreme-like events (Figure 21.9). A funnel shape for the Sudbury Igneous Complex, favoured by Naldrett and Hewins (Chapter 10, this volume), could have resulted from or been partly controlled by the channelway and explosion crater morphology. The Sudbury Igneous Complex intruded imperfectly along the "contact" between the Footwall Breccia and Basal Member of the Onaping Formation. Assimilation and/or stoping by the Complex removed most traces of Footwall Breccia in the hanging wall and essentially all of the Basal Member in the Footwall. The granophyres also had a notable effect on the Basal Member by forming part of its matrix as previously outlined. Further brecciation during various intrusive and/or tectonic phases could account for igneous stringers and patches in the Basal Member as well as mineralized Footwall Breccia containing sulphide fragments (*compare with* Coats and Snajdr, Chapter 14, this volume).

Noritic rock found in gabbro sills within the Onwatin Formation (Dressler, Chapter 4, this volume) may represent xenoliths of norite or small intrusions. The gabbro may be related to gabbroic dikes within the Onaping Formation (Muir and Peredery, Chapter 7, this volume).

The relationship between the Sudbury Igneous Complex and the large sub-Sudbury Structure igneous body(ies) believed to be present (Gupta *et al.* Chapter 18, this volume) is unclear. It is quite possible that the 2 are genetically related. The inordinate volume of granophyres in the Sudbury Igneous Complex, with respect to norite and quartz gabbro, could be explained as differentiates from a much larger magma body such as the one interpreted above. This is similar to the concept suggested by Naldrett *et al.* (1970) for the Sudbury Igneous Complex, and by Davidson (1972) for the Duluth Complex.

The large hidden igneous body may be a layered mafic-ultramafic intrusion which could account for the exotic mafic and ultramafic fragments in the Sublayer units. Naldrett *et al.* (1970) postulated a deep unexposed layered part of the Sudbury Igneous Complex as a source of this material. If the source of these fragments is a layered igneous body, this would indicate the layering pre-dated intrusion of the Sublayer. The Offset Dikes were likely intruded into major fractures opened or re-opened by bulging caused by magma pressure in the main chamber. These fractures were not initially filled by the Main Mass of the Sudbury Igneous Complex because the path of least resistance during intrusion was along the Footwall/Onaping Formation contact. The Main Mass later acted as a massive body which required crustal forces to be distributed to the then weakest part of the crust, the fractures. The Sublayer intrusions may have been initiated by reactivation of diatreme-like processes (*see* Figure on the Frood Deposit, Naldrett *et al.*,

Chapter 11, this volume) or by more conventional mechanisms.

The layered intrusion may account for significant volumes of Ni-Cu-PGE mineralization, typical of such intrusions, now found in the Sublayer of the Sudbury Igneous Complex. Innes and Colvine (Chapter 3, this volume) draw analogies between the Duluth Complex and the igneous activity at Sudbury. They point out that mineralization in the Sudbury Igneous Complex is consistent with previous magmatism in the area (for example, Nipissing Diabase) and with other large, Late Archean to Proterozoic mafic complexes. The distribution of all known sulphide bodies around the Sudbury Structure does not reflect an ordered mathematical relationship (*compare with* Peredery and Morrison, Chapter 23, this volume).

Fragments of sulphide mineralization in the Onaping Formation (Muir 1981, 1983; Rousell, 1982) consist of pyrrhotite, chalcopyrite, pyrite, and sphalerite, and attest to sulphide bodies that pre-dated the units in which they lie. Depending on how much of the sulphides in the Onaping Formation occurred originally as fragments, whether remobilized later or not, there seems to be substantial amounts of sulphide that pre-dated or were concomitant with the Onaping Formation indicating a protracted history of localized mineralization in the Sudbury area as indicated by some Huronian metavolcanic/metasedimentary units (*see* Card *et al.* 1977). As such, any discussion of metal ratios and abundances in the Onaping Formation (*compare with* Peredery and Morrison, Chapter 22, this volume) is relevant to the origin of the Onaping Formation only if the source, timing, and form of the metals is determined, which has yet to be done.

Stringers of Sudbury Breccia-like material, locally present in granophyre (Burkhard O. Dressler, Geologist, Ontario Geological Survey, personal communication, 1980), were produced by brittle movement of solidified granophyre. Therefore, some types of Sudbury Breccias in the Footwall did not require a shock-metamorphic event *per se*.

Steep south-dipping faults within the Murray Fault Zone probably account for much of the post-Sudbury Structure deformation. Instead of the extension and dip-slip faulting during the Early Proterozoic, compression in the Middle Proterozoic favoured reverse faulting (Card *et al.*, Chapter 2, this volume; Zolnai *et al.* 1984). Concentric folds were formed in the Chelmsford Formation.

Model B

INITIAL SETTING

The initial setting for Model B is similar to Model A except that in this case, the Nipissing Diabase intrusions may be considered to be the direct antecedents of

the large, elongate, sub-Sudbury Structure igneous intrusion which may consist of 2 main bodies (Gupta *et al.*, Chapter 18, this volume). The smaller, more northerly body is strongly magnetic. The cause of this signature is not known. The sub-Sudbury Structure intrusion(s) may have been related to a mantle hot spot; been at least partially in their present configuration during or slightly after the Nipissing intrusions were emplaced; and caused a large-scale bulging above the present site of the Sudbury Structure.

SUDBURY EVENTS

Early Stages

Volcanism was initiated within the Sudbury Structure area as a result of partial melting of the crust overlying the main, large, hot mafic-ultramafic, sub-Sudbury Structure intrusion. This volcanism was a precursor to the Onaping Formation and supplied some of the material for it (Figure 21.9, B1). The broad compositional range of the volcanism, represented by the range of fragment compositions in the Onaping Formation, indicates magmas of 2 or more compositions. The diversity of volcanic products is represented by composite breccias, welded tuffs, fluidal blocks, and fragments of altered material in an unaltered matrix (*see* section entitled Volcanic and Plutonic Rocks Associated with the Sudbury Structure). The number and configuration of the pre-Onaping volcanic edifices is unknown.

Later Stages

In the later stages, the system rapidly or suddenly changed and began with massive violent eruptions through ring-like fissures controlled by the existing volcanic structures (Figure 21.9, B2). One possible mechanism of triggering the violent eruptions is injection of hot mafic magma from the large sub-Sudbury Structure intrusion into a cooler, volatile-saturated, compositionally zoned silicic magma chamber (Anderson 1976; Sparks *et al.* 1977; Eichelberger 1980; Rice 1981; Huppert *et al.* 1982). This results in "flashing" and "rollover" of an unstable system (Rice 1981) leading to violent vesiculation and Plinian eruptions with resultant ash-flows displaying features of mixed and partly mixed magmas.

Large-scale doming and collapse related to the large sub-Sudbury Structure intrusion, and associated with rapid release of gases in one or more stages, would have created Sudbury Breccia bodies (*compare with* Speers 1957).

The shock-metamorphic features would have to be produced at this stage. The mechanism is hypothetical and such features are not reported from normal volcanic environments of this sort. Possible gas-driven fluidized masses much the same as outlined in Model

A, but rising through a volatile-saturated magma chamber, may have been involved, as suggested by the arrow joining B1 with A1 in Figure 21.9. Such an occurrence would form unusual products.

The resultant ash-flow eruptions through fissures would destroy some part of the pre-existing volcanic deposits and incorporate fragments of these units along with numerous wall rock fragments and fragments showing evidence of partly mixed magmas. Fragments of the pre-existing volcanic rocks could include altered rocks from vents, fissures, and hydrothermal systems, and may have included sulphides.

During the large-scale ash-flow eruptions, rapid, massive, caldera-like subsidence would occur creating an elongate "basin" later filled with numerous pyroclastic and ash-flows to form the Gray Member. Caldera collapse breccia formed the Basal Member, similar to strong brecciation of Footwall rocks at some ring dike complexes (Reynolds 1956).

An interval of unknown duration occurred between deposition of the Gray and Black Members (Figure 21.9, B3). Irregularities in the contact between the 2 members, which is locally sharp, suggest some erosion took place. Infusion of more mafic magma likely from the sub-Sudbury Structure igneous body, into the compositionally zoned chamber may have initiated further eruptions. Because the more felsic material had largely been erupted (that is the Gray Member) more mafic material would erupt and form the ash-flows of the Black Member. Genetically related spherulitic and flow-banded dikes followed.

POST-SUDBURY EVENTS

The remaining events are as discussed for Model A (Figure 21.9, B4).

SUMMARY AND CONCLUSIONS

Beales *et al.* (1967) stated, in regard to interpretation of astroblemes, "We would have to agree that in practically all cases [of interpreted meteorite impacts] a great deal of vital information is still lacking...it is necessary to rely for our conclusions on considerations of general probability combined with the gradually accumulating weight of evidence for or against a given hypothesis." Keeping this in mind, the following aspects are summarized:

1. The impact model has a number of serious drawbacks which include specific geological and structural relationships and the inability to meet certain requirements.
2. Evidence exists from a number of geological structures that endogenic shock metamorphism has occurred, such as in the Vredefort Structure which has some similarities to the Sudbury Structure. Shock metamorphism is likely not possible in "normal" (that is, common) volcanic environments.
3. Shatter cone orientations around the Sudbury Structure cannot be used as evidence supporting an impact origin.
4. The geological relationships required to be fortuitous for an impact origin are far too numerous to be rejected as circumstantial, particularly when their combined probabilities of occurrence are considered.
5. Several structural relationships indicate the Sudbury Structure and its antecedent craters were never circular or nearly circular. Arguments for the polygonality of the original crater(s) are not relevant to this conclusion.
6. The Offset Dikes were likely intruded into pre-existing fracture systems that were regional and in most cases were not directly associated with the formation of the Sudbury Structure.
7. The Sudbury Structure is spatially and/or temporally associated with the following crustal features: an active (at that time) major crustal discontinuity, the Great Lakes Tectonic Zone-Murray Fault Zone, along which protracted and/or episodic plutonism, volcanism, sedimentation, deformation, and metamorphism have occurred; a curvilinear regional positive gravity anomaly; large, elongate, positive magnetic anomalies which are north of and near the Grenville Front Boundary Fault; and an adjacent younger cryptoexplosion structure (Wanapitei Structure), which is subconformable to, but not responsible for, the shape of the East Range.
8. The Sudbury Structure is spatially associated with the following lithologic units and structures: several Late Archean/Early Proterozoic Gabbro-Anorthositic Gabbro Intrusions and Early Proterozoic granitic plutons; medium to high-grade gneisses, migmatites, and amphibolites in much of the North and East Range Footwall rocks; a discontinuous incomplete semicircle of outliers of downfaulted synclines of Huronian metasedimentary rocks to the north and northwest. Field evidence indicates the uplifted gneissic complex and the outliers are related to pre-Sudbury Events tectonism.
9. The Sudbury Structure is genetically associated with volcanic rocks now present as the Onaping Formation. The volcanic features are numerous and establish that the formation was the result of multiple explosive events involving a magmatic component.
10. The Sudbury Igneous Complex was initiated and entirely produced by endogenic processes and is not completely unique when compared to other large igneous complexes. The Melt Bodies of the Onaping Formation are directly or indirectly re-

lated genetically to the plagioclase-rich granophyre of the Sudbury Igneous Complex and show evidence of assimilation of country rocks.

11. The processes and products of diatremes, kimberlites, maars, tuff rings and cones, resurgent calderas, and ring-dike complexes have some features in common with the Sudbury Structure. The main difference in many cases is the scale of the structure, and in all cases is the absence of shock-metamorphic features, which are associated with the Sudbury Structure. No single process clearly serves to explain the origin of the Sudbury Structure. The Sudbury Structure was a product of several events and processes which have been in part superposed rendering complete similarities to any one type of structure improbable.
12. Precise mechanisms that result in endogenic shock metamorphism remain enigmatic. A mechanism akin, but somewhat dissimilar to, diatreme formation is favoured. The process involves large quantities of hot, high-pressure gases with catastrophic sudden release of energy in a near-surface environment. Subsequent volcanism and plutonism modified the original structure.

Two models are presented in this paper which make use of the processes and products outlined in points 8, 9, 11, and 12 above. More than one model was included because of the complexity of Sudbury geology and the numerous unestablished geological relationships critical to formulating a specific model. The models are to be considered in a spectrum of solutions.

The origin of the Sudbury Structure remains contentious, partly because of the complex, incompletely understood geology, and partly because of fundamental differences in philosophy of approach to geological problems by workers in the Sudbury region. Most of the differences centre on the presence of shock-metamorphic features. The author feels that the only strong point in favour of a meteorite impact origin for the Sudbury Structure is the presence of these features. Virtually all other aspects of the Sudbury Structure can be reasonably explained using known endogenic processes; several of these aspects simply conflict with an impact model.

What weight should be given to the shock features? Chamberlin's method of multiple working hypotheses (Chamberlin 1890) is no less appropriate to this case than to any other case. One need not forget examples of presumably established geological relationships, or any scientific relationship for that matter, that subsequent research showed to be incorrect. The author cannot reject the possibility of an endogenic origin for the Sudbury Structure simply because of his, or anybody else's, inability to clearly define or demonstrate the actual mechanism(s) that could produce

endogenic shock because it is so evident that there are too many features that do not seem to fit an impact model. The lack of a quantitative presentation for the proposed endogenic models in this paper is not a positive point for the presentation, but it avoids the pitfalls of accepting certain numerically "demonstrated" interpretations which are based on several interconnected assumptions.

Nor on the other hand does the author dismiss the severity of this inability to define the endogenic shock mechanism(s), for it remains the greatest obstacle to proving an endogenic origin. However, the author is encouraged by the proposed evidence of endogenic shock at such structures as the Vredefort Structure. If endogenic shock metamorphism is possible and if it is only associated with cryptoexplosion structures (that is, not 'normal' volcanism), then we forever preclude establishing proof of its existence if we interpret all cryptoexplosion structures to be the result of impact.

Many geological questions remain unanswered at Sudbury, thus no proof of the origin of the Sudbury Structure is forthcoming. All that can be done at present is to evaluate what is known and interpreted and then accept, modify, or reject any given model. Occam's Razor is appropriate. The author is reminded of the saying "What can happen, does", which is of course appropriate to all sides of the controversy regarding the origin of the Sudbury Structure.

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CHAPTER 22

Discussion of the Origin of the Sudbury Structure

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Inco Limited, Sudbury

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INTRODUCTION

The Sudbury Structure has been interpreted as the consequence of meteorite impact or of an endogenic explosion of uncertain origin. The authors of this chapter favour an impact origin. The arguments that have been presented in the past to support such an origin are reviewed. The authors also discuss arguments to the contrary and point to what they regard as weaknesses in alternative theories. In conclusion, the authors present what they regard as the most logical sequence of events in the development of the Sudbury Structure.

SHOCK METAMORPHISM

Shock metamorphism is present in the country rocks surrounding the Sudbury Structure, is closely associated with Sudbury Breccia, and is also ubiquitous and abundant throughout the Onaping Formation. In terms of the intensity of shock metamorphism, the pressure effects are dominant at the lower end of the scale and the temperature effects are minimal. In the intermediate levels, the temperature features become more significant. At the high levels, the temperature features are dominant and the end products apparently begin to

simulate volcanic materials. The shock pressure and temperature features have been collectively referred to as shock metamorphism (French 1967), and have been subdivided into 4 groups (Peredery, *see* Discussion in Chapter 7, this volume).

The first group includes the decorated planar elements occurring in quartz, feldspars, and other minerals. These are present in the Superior basement rocks up to several km from the contact with the Sudbury Igneous Complex and are also present in rock fragments in the Sudbury Breccia (Dressler, Chapter 6, this volume; Dence 1972). Planar elements abound in the country rock fragments in the Onaping Formation (French 1967, 1968, 1972a; Peredery 1972a, 1972b). Up to several sets of planar elements can be present in a single quartz grain. The number of sets of planar elements in quartz has been used elsewhere, and in the Sudbury Structure, to estimate the intensity of shock pressure (Robertson 1975; Dressler, Chapter 6, this volume).

The megascopic features of shock metamorphism, the shatter cones (Dietz and Butler 1964; Bray *et al.* 1966) are included in this group. Planar elements in quartz are also associated with shatter cones (French 1968).

Rocks which have minerals showing devitrification and very fine grained mosaic textures reminiscent of the original glassy state of these minerals are included in the second group. Rocks having such textures in minerals have been interpreted to have reached the maskelynite level of shock metamorphism (French 1967; Peredery 1972a) and have been subsequently recrystallized. This level of shock metamorphism has been reported in the Superior basement rocks and in fragments of the Sudbury Breccia (Dressler, Chapter 6, this volume). Many of the country rock fragments in the Onaping Formation have also reached the maskelynite level because the feldspars commonly show devitrification textures, and the associated quartz grains have multiple sets of planar elements, or have a mosaic or granular recrystallization pattern. Within the mosaic pattern, no planar elements are evident, but within the granular recrystallization, relicts of planar elements are locally well preserved (Muir and Peredery, Chapter 7, this volume).

The devitrification and mosaic recrystallization after feldspars and quartz in the complex glasses of the Onaping Formation similarly suggest that these rocks reached the maskelynite level (French 1967; Peredery 1972a). Planar elements in quartz are infrequently preserved in these glasses, and occur only as relicts.

The third group comprises rocks showing high pressure and temperature effects, such as the melting of sphene and zircon, vesiculation, plastic deformation, and partial melting of rocks. These effects produce flow banded heterogeneous glasses (fluidal

glasses), (French 1967, 1968, 1972a, 1972b; Peredery 1972a). These features are common in the country rock fragments, and in the complex and fluidal glasses of the Onaping Formation. Similar features have been reported also in the basement rocks (Pattison 1979; Dressler, Chapter 6, this volume), but are apparently not common.

The fourth group comprises rocks which have been totally melted. These rocks have igneous textures and are known as impact melt (Peredery 1972a, 1972b), or are finely quenched, inhomogeneous, and have been referred to as fluidal glasses. They are similar to fluidal glasses produced by partial melting. These rocks are common in the Onaping Formation. Their existence in the Footwall rocks is suspected, but they have not been positively identified in that environment.

The distribution of shock metamorphism in the Superior basement rocks and the Huronian Supergroup rocks peripheral to the Sudbury Structure corresponds approximately with the distribution of shatter cones. The outer limit of the area with shock features is approximated by an ellipse, one axis of which is about 85 km long and the other is about 50 km long. Together with the Onaping Formation, the total volume of rocks subjected to shock metamorphism in the Sudbury Structure is conservatively estimated to be about 74 000 km³.

The authors emphasize that the discovery of shatter cones in the Sudbury Structure (Dietz and Butler 1964) initiated a new interest that eventually led to the discovery of other shock-metamorphic features (French 1967). The orientation of shatter cones has been measured (Bray *et al.* 1966) but their present attitudes, especially on the South Range, are probably not original because the South Range was deformed in the Penokean Orogeny. The present authors believe that the shock metamorphism occurred before the peak of the Penokean Orogeny. Penokean metamorphism is clearly superimposed on the South Range and obliterates the shock metamorphism by recrystallization.

Fleet (1979) on the basis of petrographic analyses, interpreted that shatter cones at Sudbury developed as a result of the Penokean Orogeny. Pattison (1980) has refuted this interpretation. Furthermore, Fleet's interpretation seems to be in conflict with the restricted occurrence of shatter cones around the Sudbury Structure, and in the Superior basement rocks apparently unaffected by the Penokean Orogeny.

The presence of shatter cones in some of the country rock fragments in the Onaping Formation (Dietz 1972; Peredery 1972b) was not taken into account in Fleet's study. From the authors point of view, since shatter coning is an integral part of shock metamorphism, their presence in the Onaping Formation is as predictable as all the other shock features.

Shatter cones have been found at Meteor Crater in Arizona (Dietz 1968). Shatter cones have also been reported in the historic craters caused by a meteorite in 1947. A large meteorite disintegrated in the atmosphere and produced a whole series of small and large craters near Sikhote Alin in Siberia (Khryanina 1981; Krinow 1970).

The state of preservation of shock-metamorphic features in the Sudbury area varies considerably and depends on the regional metamorphism, tectonism, and the thermal effects related to the Sudbury Igneous Complex magmatism. On the South Range, the effects of the Penokean Orogeny have had a tendency to destroy evidence of shock metamorphism in the Footwall rocks, Sudbury Breccia, and Onaping Formation. Thus, the planar elements are generally lacking in these rocks, but evidence of devitrification in minerals is locally well preserved in the relatively less deformed rocks.

The Sudbury Igneous Complex thermal effects are evident in the overlying Onaping Formation (Peredery 1972a) and in the Footwall rocks (Dressler, Chapter 6, this volume). The Basal Breccia in contact with the Complex commonly shows a strong recrystallization which tends to destroy planar elements in minerals, whereas the devitrification textures remain relatively unaffected. The fine-grained granular recrystallization observed in the glasses of the Gray Onaping Member are detectable for as much as 200 to 300 m from the upper contact with the Complex. A similar thermal aureole in the Footwall rocks, which is observed on the North Range, had a tendency to recrystallize the planar elements. Farther away from the contact they appear to be better preserved (Dressler, Chapter 6, this volume).

The spectrum of evidence for shock metamorphism recognized in the Sudbury Structure is in many aspects analogous to those features found at well established impact structures, such as the Meteor Crater in Arizona, or the Ries Structure in Germany. In all impact structures, shock metamorphism is developed on a large scale. Sudbury is a prime example of this. There are differences between these impact structures. This should not be a surprise considering the vastly different ages of these structures, and their sizes.

The planar elements are essentially the same in all impact structures, but at Sudbury, because of the regional metamorphism, they have healed and are now called decorated planar elements. The counterparts of the glassy minerals of other structures, of the maskelynite level of shock metamorphism, are the devitrified feldspars and quartz at Sudbury. The high temperature shock features, such as the fluidal glasses, are analogous to the heterogeneous glasses in the Ries Structure, or the fused country rocks at the Meteor Crater in Arizona. The impact melt at Sudbury has its

counterpart in the Ries Structure, and also at the Meteor Crater in Arizona where it is known as impactite. The relative abundance of an impact melt at an impact crater has been shown to be a function of the size of the crater (Dence 1971).

ONAPING FORMATION

The Onaping Formation which overlies the Sudbury Igneous Complex is perhaps the most controversial of all the Sudbury rocks and is central to any discussion on the origin of the Sudbury Structure. From the earliest time, there was little agreement among the geologists studying the Onaping Formation, and this eventually led to 2 distinct schools of thought on its origin. One is the endogenic school and the other is the exogenic school. The endogenic theory emphasizes the regional setting of the Sudbury Structure and the apparent volcanic aspects of the Onaping Formation. It attaches relatively little importance to the shock-metamorphic evidence, and suggests that these features can be generated endogenically. According to the exogenic theory, the Onaping Formation is interpreted to be a huge blanket of fallback debris resulting from a giant meteorite impact. The main argument for this theory is based on the presence of shock metamorphism and the inability of volcanic or tectonic processes to produce shock-metamorphic features. The apparent volcanic aspects of the Onaping Formation are attributed to the extremely high shock pressures resulting in the high temperature effects superimposed on the country rocks.

There are some geologists who accept both the endogenic and the exogenic processes, and propose meteorite impact induced endogenic volcanism (Thomson 1969; Muir 1982). The theory of meteorite impact induced magmatic activity in the Sudbury Basin has also been discussed by French (1970). French considered that the Sudbury Igneous Complex magmatism was triggered by the meteorite impact, and that the intrusion could have had an extrusive equivalent which was later completely eroded. French believed that the rocks in the Onaping Formation itself, however, are the direct products of the meteorite impact. The authors of this chapter support this interpretation.

The stratification in the Onaping Formation is on a very gross scale (Peredery, *see* Discussion in Chapter 7, this volume). This in itself cannot be taken as direct evidence in support of the endogenic or the exogenic theory. The endogenic point of view would indicate that this is another example of the extreme magnitude of the pyroclastic deposits. From the exogenic point of view, the process of fallback dictates that the accumulated debris should be rapid, largely unsorted, and heterolithic. The Gray Member in particular meets these requirements.

What is unusual in the Onaping Formation is the total volume of materials that are very similar to the fallback debris in other impact craters. This could be to a certain degree explained by the peculiar set of circumstances that tended to preserve the entire section of the Formation inside the Sudbury Basin. The fact remains, however, that the fallback preserved in the Formation is much thicker than in any other authenticated or proposed meteorite impact crater. The reason for this is contained in the character of the Onaping Formation itself. Recognition of the Black Member as another cycle of deposition, the evidence that it was deposited probably in water, and reworking of materials in the Black Member, are features that suggest a possible mechanism to explain the rapid and turbulent conditions of deposition of this Member. On the basis of these features, Peredery (1972a, 1972b) proposed a tsunami-like wave action which could have brought in the fallback debris from outside the crater and deposited the debris on top of the fallback inside the crater. In this process, the original fallback inside the crater could have been locally eroded and redeposited. The bedding observed in the upper parts of the Gray Member (Muir and Peredery, Chapter 7, this volume) probably had such an origin.

The fine-grained horizon noted in the upper part of the Gray Member is continuous and marks a change in the depositional history of the Member. From the volcanic point of view, this horizon resembles ash-flow deposits, in that the horizon has great lateral continuity and abundant shard-like glassy fragments. Nevertheless, if the lateral continuity of this unit and its thickness (20 to 50 m) is considered, it has no planar bedding which is contrary to what would be expected if it had represented an explosive volcanism. This unit has a gradational contact with the underlying unsorted debris and consists of essentially the same materials as the bulk of the Gray Member, indicating that the unit is part of the Gray Member and was deposited in the last stages of the event.

The Basal Member has no comparable counterpart in volcanic terrains. From the meteorite impact point of view, the Basal Member could be interpreted as an autochthonous breccia (South Range) or an allochthonous breccia (North and East Ranges), and has been compared to the Bunte Breccia at Ries Crater (Peredery 1972b). The rocks in the Member have been either ballistically transported, or moved in an avalanche-like fashion along the crater wall or floor. Slumping from the crater wall could account for lenses of similar breccia in the Gray Member. Abundant evidence of shock metamorphism in the Basal Member connects it genetically to the meteorite impact and the cratering process.

The Gray and Black Members lack welded textures between glassy fragments. This is inconsistent

with a glowing avalanche or an ash-flow interpretation (Williams 1957; Thompson 1957; Stevenson 1972). The common observation of truncated flow-lined glasses indicates they were largely solidified at the time of their deposition. Fragmentation of glasses, therefore, occurred at the time of their deposition or prior to deposition.

The size and shape of the glassy fragments vary tremendously throughout the Gray and Black Members (Muir and Peredery, Chapter 7, this volume; Peredery 1972a). Some blocks that are m in diameter also show truncated flow lines just as smaller fragments. To the authors knowledge, such features present on such a large scale in the Onaping Formation are not known in the literature on volcanic rocks. In the authors interpretation, such features are indicative of the highly turbulent conditions during deposition and are consistent with the phenomena associated with meteorite impact.

The glasses in the Gray and Black Members have petrographic and chemical features that are either not known or are atypical of pyroclastic rocks. The complex glasses are probably the devitrified and recrystallized equivalents of the tethomorphic (diaplectic) minerals converted to glass in a solid state by shock metamorphism (French 1967; Peredery 1972b). Collectively, the complex glasses are the most abundant in the Onaping Formation (Peredery 1972a). Such glasses are not known to occur in volcanic rocks.

The fluidal glasses are characterized by fluidal domains which are petrographically and compositionally variable. Their chemical variation in terms of various oxides is very wide and has been discussed by Peredery (*see* Discussion in Chapter 7, this volume). Peredery argues that such a variation is not likely to be a product of alteration, but is rather, a primary feature. Such glasses with extreme chemical variation are not known to occur in volcanic rocks. However, they do occur in the fallback at Ries Crater, and other impact structures.

The fluidal glasses of the Onaping Formation do not have phenocrysts, as is common in volcanic glasses, but instead carry up to several percent inclusions of finely pulverized rock and mineral fragments. Some of these have shock features. The ubiquitous presence of inclusions in the fluidal glasses throughout the Gray and Black Members is a characteristic feature of the Onaping Formation, as well as fallback breccias from other impact structures (French and Short 1968). In volcanic glasses, although inclusions can be present, their frequency of occurrence or their distribution pattern is unlike that in the Onaping Formation.

The whole-rock chemical approach in the study of the Onaping Formation (Muir and Peredery, Chapter 7, this volume) is an attempt to broadly categorize the

rocks. The individual analyses probably approximate what the bulk compositions might be in a given area. Various plots, however, do indicate certain trends in some of the oxides. For example, in the lower section of the Onaping Formation, there is an apparent enrichment in Na_2O and a depletion in K_2O . These trends could be a function of the metasomatic alteration in the glasses and could be related to the alteration haloes associated with the Melt Bodies (Peredery 1972a), or perhaps the upper part of the Sudbury Igneous Complex.

A general trend indicated by the differentiation index, and complemented by the Specific Gravity Index, suggests a more mafic upper part than the lower levels of the Onaping Formation. This is in agreement with the field and petrographic observations which indicate that in the upper levels, the shard-like glass fragments are commonly chloritized.

All the other elements behave in an erratic pattern consistent with the heterolithic nature of the analyzed rocks.

Field observations indicate that the Melt Bodies flowed like lavas, or they were emplaced as intrusions in the Gray and Black Members (Muir and Peredery, Chapter 7, this volume). Their discontinuous distribution along the lower part of the Gray Member suggests some kind of control. The nature of this control is not clear. It does not appear to be a topographic feature in the Basal Member. Nor is there any indication in the Gray Member, either in terms of a tectonic feature or topography, to suggest such a control. Our impression is that the Melt Bodies were emplaced as intrusions along the contact between the Basal and Gray Members from which tongues of Melt protrude into the Gray Member in lava-like fashion, or as intrusions.

The mineralogy of the Melt Bodies has been discussed by Peredery (1972b). Chemically, the clinopyroxenes show no obvious differentiation trends and appear to have essentially a quench history. The analyses plot in a field occupied by the Sublayer norites and some of the norites of the Sudbury Igneous Complex (Peredery 1972b). The plagioclases show extensive alteration to albite and chemically plot in the albite field (Muir and Peredery, Chapter 7, this volume). However, normative calculations indicate intermediate plagioclase compositions.

Whole rock chemistry of the Melt Bodies indicates considerable variation in their compositions (Muir and Peredery, Chapter 7, this volume). The Melt Bodies could have been originally homogeneous and could have been subsequently contaminated by the abundant country rock inclusions. Or these bodies could have been inhomogeneous from the beginning. However, we prefer the latter explanation as there are some features that support this. For example, apophyses of fluidal glass closely associated with the margins of Melt Bodies are clearly heterogeneous. Peredery (1972a, 1972b) further argued that the short crystallization history of the Melt was not conducive to extensive assimilation to account for compositions ranging from rhyolite to andesite.

A plot of the Melt rocks and fluidal glasses in terms of FeO/MgO and CaO/MgO versus $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{MgO}$ (see Muir and Peredery, Chapter 7, this volume) serves to illustrate 2 important points. This plot indicates an overlap between the fluidal glasses and the Melt rocks and points to a common genetic relationship between them. The plot of the fluidal glasses also illustrates the variability of these glasses from fragment to fragment, and the extreme variation that exists in some of the samples analyzed.

On the basis of these features, our conclusion, therefore, is that the Melt Bodies could be impact melt. If these bodies are related to the impact melt, then their compositions should reflect the composition of the target rocks which would be mixed in some proportions. The Melt rock compositions can be closely approximated (Peredery, see Discussion in Chapter 7, this volume; Peredery 1972a) by calculations using a combination of various compositions of Superior basement and Huronian rocks. The best approximations further indicate that the rocks involved in the production of impact melt at Sudbury were mainly Superior basement granitic rocks, gneiss, gabbro, Huronian granitic rocks, and Nipissing Diabase. The Huronian metasedimentary rocks were either not involved in melting or their contribution to the impact melt was minor.

The origin of the carbonaceous material in the Onaping Formation has been discussed by Peredery (see Discussion in Chapter 7, this volume; Peredery 1972a). Its origin is not certain, but it is closely associated with the history of the Black Member and requires additional studies.

Other peculiar features exist in the Onaping Formation, but these are not central to the theme of this discussion. The authors should mention the so-called mud-ball structures which are well developed in the Black Member (Peredery 1972b). Their origin is not certain. The authors should also mention the minor but ubiquitous sulphides throughout the Onaping Formation. The sulphides have been described either as fragments (Rousell, Chapter 9, this volume; Muir see Discussion in Muir and Peredery, Chapter 7, this volume) or as secondary replacement sulphides (French 1972b; Peredery 1972b). The origin of the metals in the sulphides is not known and requires further studies.

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SUDBURY BRECCIAS

The Sudbury Breccia, described as a pseudotachylite (Dressler, Chapter 6, this volume; Speers 1957), is the

most widespread and abundant of the breccia types in the Sudbury area (Figure 22.1). The Sudbury Breccia occurs up to 50 km to the north of the Sudbury Igneous Complex contact, to the northeast up to 80 km from the contact, and to the southwest up to 50 km from the contact. South of the Complex, Sudbury Breccia occurs in Huronian rocks as far as the Grenville Front. Thus, the Sudbury Breccia occurs in a roughly circular area having a diameter of about 190 km. The distribution of the Breccia peripheral to the Sudbury Structure leaves no doubt that the Breccia is related to it.

Speers (1957) proposed a doming mechanism and magmatic degassing associated with the intrusion of the Complex to explain the distribution of the Breccias. In space, the brecciation and the magmatic activity seemed to be related, and hence the latter was assumed to be the cause of the former. However, the brecciation is an event that preceded magmatism; field relationships clearly indicate this. Speers speculated on a complicated sequence of brecciation before and after the magmatism, but did not present any clear evidence of Sudbury brecciation postdating the magmatism. All evidence indicates that the Sudbury Breccia was formed before the Sudbury Igneous Complex was intruded. This, combined with the unusually large areal distribution of Sudbury Breccia, suggests that a

special set of conditions existed in the area prior to the Sudbury magmatic activity.

The Sudbury Breccia postdates the Nipissing magmatism as it clearly crosscuts the Nipissing Diabase. The Sudbury Breccia is different from the intrusive breccias in that it has a matrix with a chemistry which is a mixing product of the adjacent host rocks (Speers 1957; Card 1978a; Dressler, Chapter 6, this volume).

Within the thermal aureole of the Sudbury Igneous Complex, the Sudbury Breccia shows metasomatic and textural changes (Speers 1957; Greenman 1970; Hebl 1978; Dressler, Chapter 6, this volume). The total effect of these changes produces a rock that is similar to the Footwall Breccia described by Greenman (1970) and Pattison (1979). Whether or not some or all of the Footwall Breccias were formed by this process is not certain. Alternatively, there may have been allochthonous breccias, similar to those in the Basal Member, in contact with the Footwall rocks of the Sudbury Structure. Such breccias may have been thermally metamorphosed and in places may have been made conducive to mobilization by the heat of the Sudbury Igneous Complex, by the pressure of the volatiles, or by the instability of the Footwall.

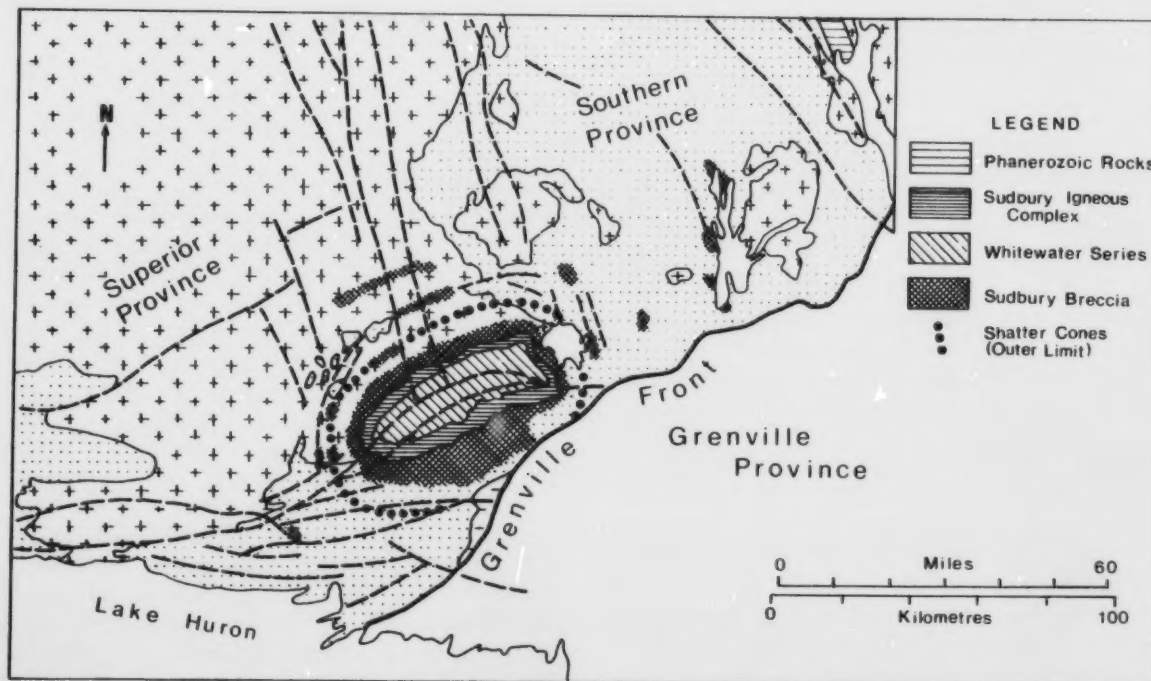


Figure 22.1. Distribution of the Sudbury Breccia and shatter cones in the Sudbury area. Note the concentric faults on the East and North Ranges of the Sudbury Structure.

The distribution of the Sudbury Breccia is fairly ubiquitous throughout the country rocks of the Sudbury Structure, but the amount of breccia and the intensity of brecciation are variable. Within a few km of the Sudbury Igneous Complex contact, the volume of Sudbury Breccia is large. Farther away from the contact, zones of relatively unbrecciated country rock alternate with zones of intense development of Sudbury Breccia. Dressler (Chapter 6, this volume) discusses zones of intense Sudbury brecciation at distances ranging from 18 to 50 km from the Complex. So far, no particular pattern in the distribution of these zones of intense brecciation has been demonstrated. Dressler (Chapter 6, this volume) and Card (1978a), however, both suggest that the zones may be distributed around the Sudbury Structure in both radial and concentric patterns.

No known counterpart in any volcanic terrain on earth is comparable in terms of the intensity of the development of Sudbury Breccias and the areal extent of brecciation at Sudbury. If magmatic degassing was the cause of brecciation, as was suggested by Speers (1957), then the magma chamber that produced the gases must have been of very large proportions and must have been fairly close to the rocks being brecciated. If this were the case, the magma could have been assumed to have utilized the brecciated zones to rise to the surface. Under these conditions, abundant magmatic material associated with the breccias, as well as other volcanic manifestations, would be expected. The authors are not aware of any evidence of volcanism associated with Sudbury Breccias.

The offset dikes appear to have utilized to some extent, the weaknesses created by brecciation (Grant and Bite, Chapter 12, this volume). The Frood-Stobie Offset is entirely in Sudbury Breccia, and this seems to be the case for the Manchester Offset, but others have little associated Sudbury Breccia with them and cross-cut the breccia.

The presence of shock metamorphism in Sudbury Breccias as well as in country rocks (Dressler, Chapter 6, this volume) is another distinctive feature not reported in breccias in volcanic terrains or in intrusive breccias, or for that matter, in any volcanic rocks. These shock effects occur in a zone up to 20 km wide that is peripheral to the Sudbury Structure.

Recognition of at least 3 types of Sudbury Breccia (Dressler, Chapter 6, this volume) underlines the complexity of the problem. Generally, weak shock features are closely associated with the massive type of breccia, and the authors are inclined to think that this Breccia was a direct product of the shock wave. Not all massive Sudbury Breccias have shock features associated with them. This could be because the shock wave is gradually attenuated as it travels through a rock. At the source of the shock wave, the intensity is

great, but farther away as the shock wave is attenuated, the pressure effect on the rocks are in the same order of magnitude as those effects produced by normal endogenic processes. But even in this latter case, the brecciation process has produced peculiar results consisting of intense *in situ* milling. In volcanic environments, intense milling in place is either lacking or is unusual, whereas in tectonic environments, it is common but includes considerable translation movement tending to produce mylonites.

A second variety of Sudbury Breccia with well developed flow lines could belong to the category of tectonic mylonites. Generally, the shock features are uncommon, or are absent in these breccias. Not all rock fragments in these Breccias originated in the adjacent country rocks. This feature, combined with the fluidal character of the matrix, suggests that considerable movement occurred in the Breccia zones. Such Breccias could have been produced in response to isostatic adjustments immediately after excavation of the transient crater by meteorite impact. The process is essentially tectonic and can be regarded as an indirect product of the impact. Together with impact, these isostatic adjustments are responsible for the final configuration of the impact crater structure.

A third type of breccia with an igneous-looking matrix is mineralogically very similar to the massive pulverized matrix type. This feature and the close association of the 2 types of Breccia suggest a close genetic relationship between them. The authors propose that the igneous-looking matrix could have been derived by melting of the pulverized matrix of Sudbury Breccia. Variation in the texture of the igneous-looking matrix could be the result of different degrees of melting of matrix materials; this in turn could be a function of the composition of country rocks and the temperature they attained during pulverization.

The distribution of Sudbury Breccia provides evidence as to the original size of the Sudbury crater basin. In other impact sites, the most intense brecciation is generally below the crater structure. The shatter cones are similarly distributed below the crater structure. If this is also the case for Sudbury, and if the Sudbury crater basin had to cover all the areas with shatter cones and intense brecciation, then, the diameter of the basin would have to be about 190 km. French (1972b) estimated that the diameter for the Sudbury crater basin is about 100 km. The Sudbury Basin (as defined in this volume) is probably the transient crater modified by isostatic adjustments and igneous activity of the Sudbury Igneous Complex. The authors postulate, therefore, that the rim of the Sudbury crater basin (see Figure 22.6d) corresponds approximately to the outer zone of Sudbury brecciation and is also marked by intense fracturing and faulting.

COLLAR AROUND THE SUDBURY STRUCTURE

Rocks in the Footwall of the Sudbury Structure have lithological, metamorphic, and structural features that set them apart from other rocks in the Sudbury area. These rocks form a ring or a collar up to several km wide.

North and East Ranges

Here, the Footwall rocks constitute a complexly metamorphosed migmatitic assemblage of gneissic, felsic, anorthositic, mafic, ultramafic, and intrusive granitic rocks. The gneissic rocks have 2 pyroxene assemblages indicative of granulite facies metamorphism. Porphyritic gabbroic dikes cut the gneisses.

The attitudes in the gneisses, although complicated, are dominantly subvertical (Dressler, Chapter 6, this volume), and suggest a complex tectonic-metamorphic history unlike the history in the associated granitic rocks or the local Huronian sequences.

The gneissic complex has an extensive network of Sudbury Breccia pervading it. Both the gneisses and Sudbury Breccia are, in turn, cut by veins, up to several cm thick, of granitic material commonly containing abundant granophyre that is locally rich in epidote and pyrite. The presence of granophyre in the granitic veins suggests they could be related to the Sudbury Igneous Complex. It should be mentioned in passing that the field relationships clearly indicate that the granulite facies metamorphism developed much earlier than the emplacement of the Sudbury Igneous Complex, and cannot be related to this heat source.

The presence of shock features in these rocks (Dressler, Chapter 6, this volume) indicates that the gneissic rocks of the North and East Ranges are an integral part of the Sudbury Structure. The granulite facies metamorphism of the gneisses further suggests that they developed at much greater depths than their surroundings indicate, and therefore, could be part of a highly disturbed isostatic feature related to the Sudbury Structure. In the authors opinion, such an isostatic feature is a normal consequence of the unloading effects after meteorite impact.

South Range

In the South Range, the Sudbury Structure is in contact with anorthositic rocks, Huronian volcanic and sedimentary rocks, and "granites" intruding the Huronian sequence. The Huronian rocks, peripheral to the Sudbury Structure, have near vertical attitudes, consistently face to the south, are locally overturned to the south, and have a complex tectonic history. Farther to the south, folds are more open with moderate dips on the flanks.

The Huronian sequence has been affected by an

early folding event approximately coincident with the time of the intrusion of the Nipissing Diabase (2.15 Ga), and later by the Penokean Orogeny (1.9 Ga); (Sims *et al.* 1981). Further complications can be attributed to early Huronian faulting along the Murray Fault System and later reactivations along this fault system that also affected the southern half of the Sudbury Structure.

As in the North Range, the South Range rocks are pervaded by Sudbury Breccia. The Breccia has undergone low grade greenschist facies metamorphism possibly related to either the waning stages of the Penokean Orogeny, or the heat of the Sudbury Igneous Complex, or both.

By analogy to the North Range gneisses, the South Range appears to have a similar structure, but rocks of a different age were involved. The steep dipping to overturned character of the Huronian sequence, consistent top facings to the south, and the complex tectonic pattern can be interpreted as a flipped-up hinge zone of the transient crater wall.

SUDBURY BASIN MORPHOLOGY

The physical structure that contains the Sudbury Igneous Complex and breccias and sedimentary rocks of the Whitewater Series is a large depression or a deformed basin. In terms of size, the Sudbury Basin is in the same order of magnitude as are calderas, but the Basin has features which make it distinct from calderas. Morphologically, calderas are subcircular and may be multilobate (Macdonald 1972). The Sudbury Basin, however, was originally probably polygonal (Morrison, Chapter 23, this volume). Caldera walls are precipitous, whereas the walls of the original Sudbury Structure dipped inward at shallow angles (Morrison 1980). The walls of the Sudbury Structure are presently shallow to moderately dipping in the North Range, which is tectonically the least disturbed. On the South Range, the walls are moderately dipping, and locally are subvertical to overturned to the south. The steep dips and overturned attitudes are attributed to tectonism, probably the waning stages of the Penokean Orogeny.

Caldera walls are relatively massive and generally have hydrothermally altered monolithologic autobreccias locally developed. In comparison, the Sudbury Structure has an intense and extensive brecciation which reaches 10s of km into the surrounding terrain. The pseudotachylitic character of breccia developed in Sudbury is unlike that in caldera environments as was discussed earlier. In terms of areal distribution, intensity, and type of brecciation, the authors know of no caldera counterpart that could be considered to closely approximate to the Sudbury Structure.

Calderas commonly have associated ash-flow deposits which erupted through the arcuate fissures that controlled the collapse mechanism. Such feeder structures are lacking in the Sudbury Structure. Even though the Onaping Formation is considered by some geologists to be one of the world's largest ash-flow sheets (Stevenson 1972), there are many objections to this interpretation as discussed in the Onaping Formation section of this chapter.

Large troughs and terraced walls which are present in the Sudbury Structure (Morrison, Chapter 23, this volume) are generally lacking in calderas. Wherever troughs are developed in calderas, the troughs are sporadically distributed; in impact sites and at Sudbury, the troughs are symmetrically distributed. The central arch and the peripheral rhyolite domes commonly present in calderas are lacking in the Sudbury Structure. The ring dike commonly present in calderas could be equivalent to the Sudbury Igneous Complex, but the Complex does not have the configuration of a dike (Naldrett and Hewins, Chapter 10, this volume).

Comparison of the Sudbury Structure with well documented meteorite impact sites leaves little doubt as to their similarities. All of the previously discussed features present in the Sudbury Structure are typical of large impact sites as summarized by Head (1977). These include the original polygonal outline, large troughs at the apices of the polygon, terraced walls, original relatively shallow inward dipping floor of the structure, intense and extensive brecciation of Foot-wall rocks, and a direct link between this brecciation and shock metamorphism.

DEFORMATION OF SUDBURY STRUCTURE

The present-day elliptical shape of the Sudbury Structure is attributed to 4 deformation events (Morris 1980; Peredery 1972a; Dietz 1972; Brocoum and Dalziel 1974; Rousell 1975, 1976, 1981). From older to younger these deformations are as follows:

1. the Penokean Orogeny
2. the deformation associated with the intrusion of the Sudbury Igneous Complex
3. the deformation related to the Grenvillian Orogeny
4. the deformation related to the Wanapitei Lake Structure

Starting with the youngest deformation, it is presently recognized that the Lake Wanapitei Structure is a 37 Ma old meteorite impact crater (Winzer *et al.* 1976; Dence and Popelar 1972) superimposed on the Sudbury Structure on the East Range. A number of identifiable concentric faults visible on the Landsat imagery surround the Lake Wanapitei Structure. These faults cut and displace the Sudbury Structure on the

East Range as shown in Figure 22.2. This is corroborated by some of the authors geological and geophysical work on the ground. North-south striking arcuate faults distort the Sudbury Structure and can be traced for 10s of km and define a ring-like pattern around Lake Wanapitei. To what extent these faults have acted to distort the East Range of the Sudbury Structure is not known. This requires considerable further work.

As discussed earlier, paleomagnetic data suggest dips in the Sudbury Structure were originally shallow (Morris 1980). The present-day dips of the noritic unit are about 40° on the North Range, and 40° to 90° on the South Range, and locally, are overturned to the south. Their present attitudes can be attributed in part to the Penokean Orogeny for rocks on the South Range, but the rocks on the North Range do not appear to have been disturbed by this tectonic event and hence an alternative explanation is required. The authors believe that the intrusion of a large volume of magma in the Sudbury Igneous Complex and subsequent collapse of the magma chamber could have produced down-buckling or collapse of the original sheet-like body to give the apparent final configuration of a lopolithitic structure as interpreted by Wilson (1956). In this process, considerable steepening of the dips of the Sudbury Igneous Complex could have occurred.

Even though Dietz (1964) implied that the deformation of the Sudbury Structure could be in some measure related to the Grenvillian Orogeny, the studies by Brocoum and Dalziel (1974) indicated that the Grenvillian effects are minimal. The authors add that perhaps some of the faults in the Sudbury area are related to the Grenville Front because they appear to be part of the Grenville Front east of Sudbury. The faults appear to have been long-lived structural features.

Brocoum and Dalziel (1974) concluded that the deformation of the Sudbury Structure occurred in the

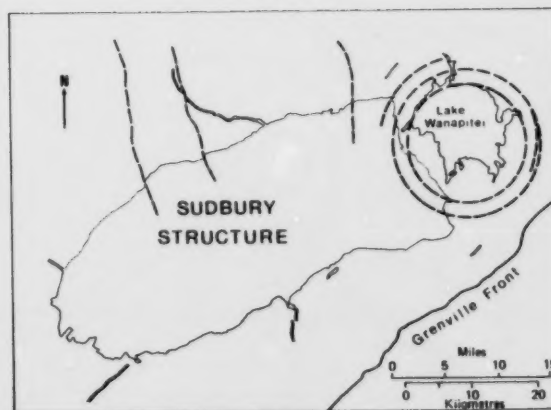


Figure 22.2. The Lake Wanapitei meteorite impact structure (37 Ma) superimposed on the Sudbury Structure on the East Range.

time interval after the intrusion of the Sudbury Igneous Complex, but before the intrusion of the olivine diabase dike swarm (1.46 Ga, Gates and Hurley 1973). However, intrusion of the Complex (1844 Ma) coincided closely with the Penokean Orogeny (1.9 Ga) and hence, it is possible that the intrusion was synchronous with the Penokean deformation. Thus, on the South Range, the Whitewater Group and the Sudbury Igneous Complex are faulted and deformed and have a similar strain fabric as the Southern Province rocks in the Sudbury area which are affected by the Penokean Orogeny (Brocoum and Dalziel 1974).

Cantin and Walker (1972) studied the paleocurrent directions in the Chelmsford Formation and concluded the Sudbury Basin was not symmetrical at the time of deposition of this formation. If the Penokean Orogeny was coincident with the intrusion of the Sudbury Igneous Complex, then possibly the Sudbury Structure was in part deformed at the time of deposition of the Chelmsford Formation. Asymmetry could have been produced either as a result of collapse of the Sudbury Igneous Complex, or by compression during the Penokean Orogeny. The timing of the Complex collapse and the Penokean Orogeny are not certain, so either one of these explanations is possible. The Penokean Orogeny could account for the renewed high energy deposition inside the Basin. The authors tend to favour the explanation that involves compression. Late waning stages of the Penokean Orogeny gently folded the Chelmsford Formation.

Rousell (1972) considered that originally the Sudbury Basin was less elliptical. Brocoum and Dalziel (1974) further argued that the original Basin was circular. Peredery (1972a, 1972b) contended that, on the basis of the shapes of known impact sites, the original shape of the Sudbury Structure was polygonal. Making a number of assumptions, and taking into account the amount of strain, particularly in the fragmentary rocks of the Onaping Formation, Peredery (1972a) calculated the degree of deformation of the Sudbury Structure on the South Range. On the basis of these data, the southern original Footwall rocks were thrust northward by about 13 km. The shape of the reconstructed Sudbury Basin is, therefore, estimated to approach a distorted polygonal body measuring about 60 by 39 km. Distortion due to faulting could increase the northwesterly axis of this body, but reliable data which could give a better estimate are lacking at present.

The evidence presented above indicates that the present-day outline of the Sudbury Structure could be a product of a number of deformational events, such as collapse of the magma chamber, Penokean folding, a complicated sequence of faulting spanning a prolonged period of time, and a recent impact structure.

LOCATION OF SUDBURY STRUCTURE

In the discussion of the Sudbury Structure (Figure 22.3), some authors suggested (Card and Hutchinson

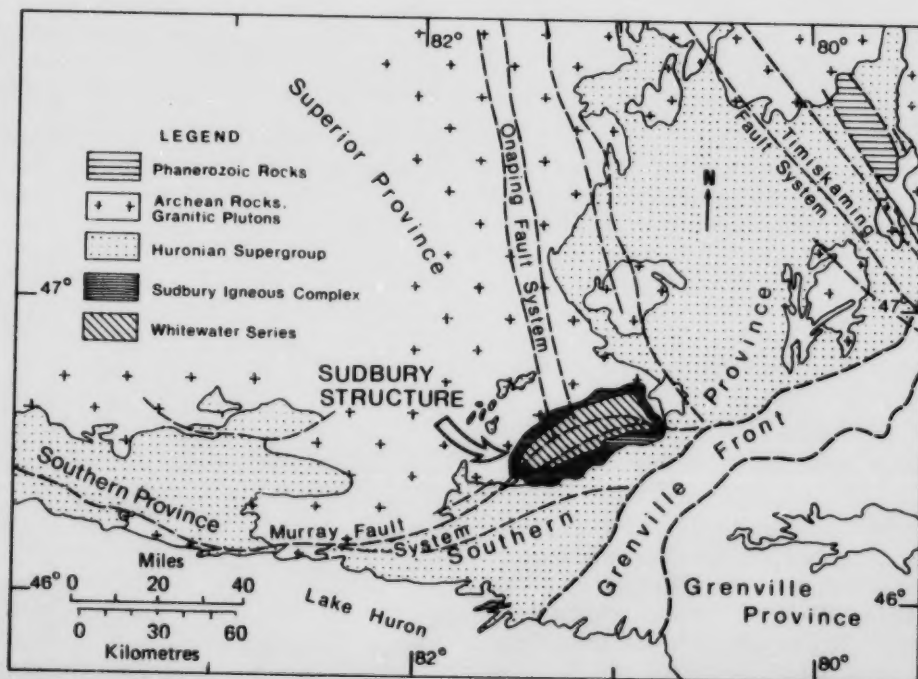


Figure 22.3. Regional geological setting of the Sudbury Structure.

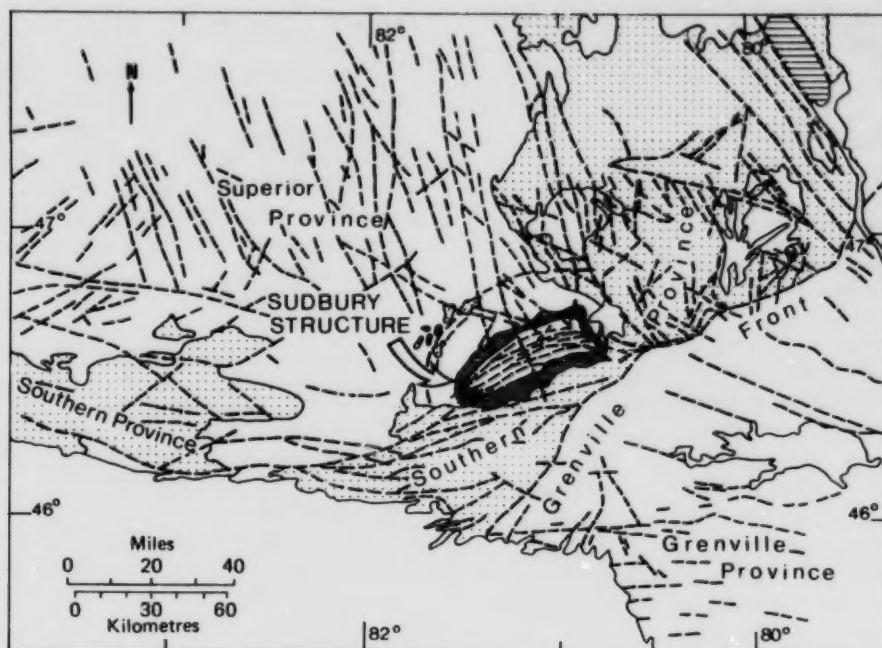


Figure 22.4. Regional fault pattern in the Sudbury area.

1972; Stevenson and Stevenson 1980; Card *et al.*, Chapter 2, this volume) that the setting in time and space of the Sudbury Structure indicates that it is more likely to be of endogenic origin rather than the product of meteorite impact. This argument is based on the improbability of a meteorite striking at the particular site of the Sudbury Structure. The present authors intend to examine the evidence further in this chapter.

Intersection of Structural Provinces

The location of the Sudbury Structure at the so-called triple junction of the Superior, Southern, and Grenville Structure Provinces of the Canadian Shield is genetically significant according to some authors. Guy-Bray (1972) noted that the Huronian cover at the time of the Sudbury Event was widespread and that the Superior-Southern boundary was probably far removed from its present location. The present location of the Sudbury Structure near the boundary between the Superior and onlapping Southern Provinces is largely a function of the depth of erosion. That is, the Sudbury Event involved both the Superior basement rocks and the Huronian cover of the Southern Province. This dictates that at some erosional level, the Sudbury Structure will appear on the boundary between these rocks; as it does at present.

The close proximity of the Sudbury Structure to the Grenville Front cannot be regarded as anything more than a coincidence. Even though there is some disagreement about the age of rocks in certain parts of the Grenville Front (Brocoum and Dalziel 1974;

Brooks 1976), the Grenville Front is generally accepted to be a relatively young tectonic feature (1 Ga) and as such, cannot have a bearing on the origin of the Sudbury Structure.

The present authors find that the argument of the location of the Sudbury Structure at the so-called triple junction of structural provinces cannot be taken as significant because a multitude of areas having triple junctions exist without Sudbury-like structures.

Intersection of Fault Systems

Card and Hutchinson (1972) regarded the intersection of Onaping-Timiskaming and Murray regional fault systems in the Sudbury area (Figure 22.4) as another indication of the Structure's endogenic origin. While it is true that this intersection exists at Sudbury, it is equally true that faults have many other points of intersection with other major regional faults far removed from Sudbury (Guy-Bray 1972). To the authors knowledge, no specific features, such as shock pressure and/or high temperature effects exist that are directly associated with these fault systems that would point to a genetic link between them and the Sudbury Structure.

Intersecting fault systems abound in many parts of the world, but none have demonstrably resulted in producing either Sudbury-like structures or developing the weakest of shock-metamorphic effects. Even though partial fusion of mylonitized material along certain faults has been reported in the literature (Ermanovics *et al.* 1972; Philpots and Miller 1963; Wal-

lace 1976; Scott and Drever 1953); shock effects are absent from these fault systems.

Intersecting Arches

Much has been made of the intersecting arches at Sudbury. Card and Hutchinson (1972) emphasize that the Chiblow-Baldwin Arch west of the Sudbury Structure, and the so-called Onaping Arch north of the Structure may have played an important role in the genesis of the Structure. Arching is simply a stage in the folding of rocks. If 2 arches meet, it is common that 1 arch is later than the other, and generally results in crossfolding. If the 2 arches are contemporaneous, then it must be assumed that tectonic forces had different orientations in each domain. Refolded folds are a feature of the Canadian Shield; there is no reason to attach any special significance beyond a complicated style of tectonism. The present authors emphasize that even in the most intense and complex tectonic regimes, features related to shock metamorphism have not been reported.

Stratigraphy

Card and Hutchinson (1972) further argued that the rift-controlled stratigraphy played an important role in the location of the Sudbury Structure. The deposition of sediments into an unstable basin with its concomitant accumulation of basaltic and felsic volcanic rocks in the Sudbury area is implied as if these rocks were indicators of the Sudbury Event to come. This depositional cycle lasted from 2.5 to 2.3 Ga and clearly predates the Sudbury Event by nearly 0.5 Ga. The more direct products of the instability of the depositional environment are the early major folding and intrusion of the diabases at 2.15 Ga, and the later Penokean Orogeny at about 1.9 Ga (Card 1978b). These activities predate the Sudbury Event. The Penokean Orogeny also affected the Sudbury Structure.

Volcanic Rocks

Card and Hutchinson (1972) also implied that there could be a genetic link between early Huronian volcanism and the Sudbury Igneous Complex. The Huronian volcanism and the emplacement of the Sudbury Igneous Complex are separated by a time interval of several 100 Ma. The present authors think that the Nipissing magmatism (2.15 Ga) could be genetically much closer in time to the Huronian volcanism than to the Sudbury Igneous Complex.

Furthermore, the felsic and siliceous character of the Complex is unique to Sudbury (Naldrett 1981). For these reasons, it is unlikely that a direct genetic link exists between the Huronian volcanism and the Sudbury Igneous Complex.

Paleotopographic "High"

The existence of a paleotopographic "high" in the area presently occupied by the the Sudbury Structure has been postulated and has been assumed to be significant in the geologic history of the area (Card and Hutchinson 1972). The postulated "high" has been interpreted as a domal structure (Speers 1957) that existed before the deposition of the Huronian sediments. This is based on the presence of some Huronian outliers northwest of the Sudbury Basin. Guy-Bray (1972) admitted that if the topographic "high" is proven, it would pose some problem for the astrobleme theory for the Sudbury Structure.

The premises on which this paleotopographic "high" is built will be further examined. In general, west of Sudbury in the Sault Ste. Marie-Massey area, the paleocurrents trend east to southeast, whereas in the Cobalt-Gowganda-Sudbury area they trend south to southwest. The 2 trends meet in the vicinity of Espanola, producing a new trend to the south and giving rise to an overall Y-shaped pattern (Card and Hutchinson 1972). East and northeast of the Sudbury Structure, the paleocurrents change from south to southwest suggesting some paleotopographic "high" both there and also to the south, at the present-day Grenville Front (Figure 22.5). A paleotopographic "high" apparently existed also south of the Sudbury area along the Grenville Front because the paleocurrents trend here to the west (Long 1978). Close to the eastern edge of the present-day Sudbury Structure, both south and southwest paleocurrent directions are recorded that probably indicate a changing current regime. Northwest, west, and south of the present-day Sudbury Structure, the majority of the paleocurrents trend southwest as in the rest of this region. In other words, the dominance of this southwesterly direction indicates a regional trend, and is not indicative of any significant topographic "high" in the Sudbury area. Furthermore, during deposition of the overlying Serpent Formation, the current directions changed so that in the southwest,

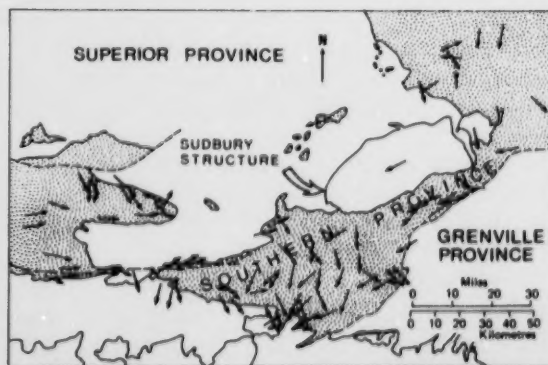


Figure 22.5. Regional paleocurrent directions in the Sudbury area.

the trends are toward the Sudbury Structure (see Figure 22.5) suggesting a topographic low in that direction.

Young (1968), who originally postulated the existence of a "weakly positive" topographic "high" at the present-day Sudbury Structure, based his inference on a limited number of observations. He noted that none of his crossbedding directions in Huronian rocks surrounding the Sudbury Structure are directed towards it. Young's (1968, p. 168) argument that the absence of Huronian rocks in the Sudbury Basin points to a "weakly positive area" is negated by the common occurrence of blocks and boulders of Huronian rocks in the Onaping Formation (Peredery 1972a; Muir and Peredery, Chapter 7, this volume) which must certainly point to their former presence rather than their absence at the site before the Sudbury Structure was formed.

Even if the existence of this "weakly positive" feature at the present-day site of the Sudbury Structure is assumed, it was probably of short-lived duration. If an erosional rate of about 1 mm/1000 years is assumed, the topographic "high" in question was probably completely eroded by the end of the early Aphebian depositional cycle (2.5 to 2.15 Ga). Later, the early Aphebian folding event at 2.15 Ga, and still later the Penokean folding event (1.9 Ga) would probably have created an entirely different topography in the area concerned. It is unlikely that some "weakly positive" topographic feature would persist through 2 orogenic events and then emerge as the Sudbury Structure nearly 0.5 Ga later.

Speers' (1957) deduction that there must have been a domal feature at the present-day site of the Sudbury Structure is based on the fact that there are peripheral outliers of Huronian rocks, as in the Geneva Lake area, partly surrounding the Sudbury Structure (see Figure 22.3). On the South Range, structural evidence for doming, however, is generally lacking, and is complicated by the Penokean Orogeny. The upright position of Huronian strata in the immediate vicinity of the Sudbury Structure is not compatible with a domal configuration. Similarly, foliations in the Footwall gneisses on the North Range are dominantly subvertical (see Dressler, Chapter 6, this volume). Therefore, neither the foliation in the gneisses nor the structure of the Huronian strata are consistent with the postulated doming.

The present authors believe that the Huronian outliers in the Sudbury area can be explained by impact mechanism. This explanation follows directly from the interpretation of the Sudbury Structure as a ringed (or multi-ringed) meteorite impact site. Large meteorite impact sites are known to have down-faulted outer ring-like structures (Dence *et al.* 1977) which are interpreted to result by collapse of the structure after

impact. The present-day distribution of the Huronian outliers is a function of the depth of erosion.

SUDBURY IGNEOUS COMPLEX

In this section, the authors present a few ideas which may have a bearing on a better understanding of magmatic history of the Sudbury Igneous Complex and the Sudbury Structure itself.

The emplacement of the Complex is considered to have followed shortly after the Sudbury Structure was formed, but the exact time interval between the formation of the Structure and intrusion of the Complex is not known. This condition arises from an inability to accurately date the impacting event (Fullagar *et al.* 1971; Marchand 1976), although the Complex itself had been dated precisely (Krogh and Davis 1974; Krogh *et al.*, Chapter 20, this volume).

The emplacement of the Complex closely followed the modified crater wall. The intrusion must have lifted the entire Onaping Formation, as there is apparently very little material in the Footwall that could be correlated with it. The magmatic activity was complex, and probably spanned a considerable time period. The chronological sequence of these activities is not very well known, and has been discussed by Naldrett and Hewins, (Chapter 10, this volume).

The paucity of impact melt in the Onaping Formation has led to suggestions that perhaps considerable amounts of it have been incorporated into the Sudbury Igneous Complex (Dence 1972). Naldrett *et al.* (1970) have similarly suggested that the siliceous character of the Complex could have resulted from mixing of the magma and the melt at the base of the crater structure. There is another possibility. If it is accepted that the impact event coincided with the Penokean Orogeny, then there must have existed a regional high thermal gradient in the area. This thermal gradient combined with the residual heat of about 200° to 300°C produced by shock loading and decompression (Stoffler 1971) could have resulted in partial or total melting of rocks below the impact site. This would be considered to be an indirect product of the meteorite impact. Dence (1972) estimated about 400 km³ of such melted rocks exist in the Sudbury Structure. This material would occur in close association with the impact melt, would be initially directly below the melt, and probably would be generally similar to the melt. Such molten material would be theoretically the first to come in contact with the Sudbury Igneous Complex magma and could be mixed with it.

The siliceous and dry character of the original noritic magma suggests that the emplacement was a relatively slow and sluggish process. Whether this noritic phase ever reached the surface appears unlikely. If it had reached the surface, there would prob-

ably be some volcanic manifestations of it, especially stratigraphically above the fallback and wash-in. There is no such evidence. Instead, the wash-in shows a progressive reworking, and gradually grades into the mudstones of the Onwatin Formation. Deposition of mudstones suggests a long and slow weathering under relatively stable conditions. The chemical composition of these mudstones indicates that these rocks were derived by weathering of the Onaping Formation (Sadler 1958). This could be taken to indicate that the crater structure was still intact at that time, and if there were any volcanic manifestations, these should have been contained within the crater structure. Their absence, therefore, suggests that no such volcanic activity took place in the time period between the deposition of the Onaping Formation and the Onwatin Formation. It should also be pointed out that there is no evidence of volcanic activity associated with the deposition of the overlying Chelmsford Formation turbidities.

The intrusion of subvertical dike-like gabbroic and melanocratic gabbroic rocks into the Whitewater Series occurred relatively late in the history of the Sudbury Structure. The intrusion of quartz diabase dikes into the basal quartzose norite, quartz diorite Offsets, and Footwall rocks is well after the Sudbury region cooled considerably (Grant and Bite, Chapter 12, this volume).

On the South Range, even though the Sudbury Igneous Complex norite is intruded into the Murray Pluton, the granitic dikes apparently stemming from this pluton are intruded into the norite. Such offshoot dikes are up to 10s of m wide and up to 100s of m in length. Since the Rb/Sr radiometric dates on the Murray Pluton clearly indicate an older age (2.23 Ga) than the Complex (1844 Ma), Gibbins *et al.* (1972) have interpreted the age of 2.00 Ga for the granitic offshoots as remobilized material caused by the intrusion of the Complex.

In addition to the granitic dikes, there are small bodies and veins of felsic rocks in all parts of the Sudbury Igneous Complex, particularly within the quartz gabbro and the overlying granophyric rocks. These probably are comagmatic with the Complex; and many of them could be related to the granophyre, or late stages of crystallization of the Complex. Gibbins *et al.* (1972) reported an age of 1.78 Ga for such felsic dikes.

The apparent absence of a central uplift in the Sudbury Structure prompted Peredery and Naldrett (1975) to suggest that the original central uplift collapsed into the magma chamber after the intrusion of the Sudbury Igneous Complex. This is in line with the paleomagmatic data of Morris (1980) which indicate that the original dips of the Sudbury Igneous Complex were less steep than they are at present. The steepening of the original sheet-like configuration of the Sudbury

Igneous Complex could also have been conducive to mobilization of the noritic fractionated liquids mixed with the impact melt and the molten country rocks. Such mixtures could have ascended along the unconsolidated or partly consolidated upper part of the Complex. Ascent of such liquids could have contributed to the amount of felsic material present now in the upper part of the Sudbury Igneous Complex.

The noritic pulse of the Complex is mineralogically similar to the Nipissing Diabase. This similarity suggests that perhaps a genetic link exists between them. The authors agree with those who claim that the Sudbury magmatism, as it is manifested in the Sudbury Igneous Complex, is a part of the regional setting, but would like to add that its uniqueness and its close relationship to the Sudbury Structure are striking and unmistakable. For these reasons, the present authors suggest that because the meteorite impacted into a tectonically active terrain, the resulting impact crater became magmatically modified. Perhaps, this sequence of events was necessary in order to generate some of the largest and richest Ni-Cu sulphide deposits of the world.

FINAL REMARKS

Recognition of the whole spectrum of shock metamorphism is clearly central to the understanding of the origin of the Sudbury Structure. Until it is demonstrated unequivocally that shock metamorphism can be caused by volcanic activity, the shock features will continue to be the criteria for identifying meteorite impact sites. Furthermore, studies on volcanic rocks indicate that near-surface volcanism is not capable of sustaining pressures high enough to cause shock metamorphism in rocks. The highest pressures attained are about 5 kbars (Gorshkov 1959), which is an order of magnitude less than that required to produce the weakest shock effects. Even in the most powerful known eruptions (Walker 1980), there is no evidence of shock metamorphism.

Experimental work indicates that extremely high pressures are required to produce shock-metamorphic features (*see* French and Short 1968; Roddy, Pepin, and Merrill 1977). These pressures are of the order of 10s to 100s of times greater than those associated with volcanism.

Additionally, it should be pointed out that nuclear experimental explosions offer similar evidence of shock metamorphism as is observed in the naturally formed meteorite impact craters. A nuclear explosion crater has a whole spectrum of features similar to that of a meteorite crater; a zone of melting, an intensely brecciated zone of high pressure shock effects, followed by a zone of weak shock, and normal fracturing

in the country rocks (Short 1968). Significantly, shatter cones have also been reported (Bunch and Quaide 1968).

However, as pointed out by French (1968), our experimental knowledge on shock metamorphism is inadequate. This condition persists to the present day. Although Horz's (1968) experiments have conclusively demonstrated that the planar elements in quartz can be produced by shock, other experiments suggest different conditions perhaps could produce similar features (Carter 1968; Baeta and Ashbee 1967; Heard and Carter 1968; Currie 1972). Planar elements could possibly have formed under conditions different from those which produced shock induced planar elements. Where these planar elements are (a) accompanied by other shock features, including the heterogeneous character of the associated glasses, and (b) have large areal distribution, their origin by shock metamorphism is beyond question. The absence of such features in normal volcanic terrains, and in highly deformed tectonic terrains, indicates that the conditions for formation of shock features are unique and different from those normally found in crustal rocks.

SUDBURY STRUCTURE MODEL

After a critical examination of the evidence and the arguments, the authors find that the meteorite impact offers the best explanation for the origin of the Sudbury Structure.

The authors' model of the evolution of the Sudbury Structure is illustrated in Figures 22.6a to 22.6e, inclusive, and its various stages of development and subsequent history are given below.

1. At the time of impact, the Penokean Orogeny was at its peak and the thermal gradient in the Sudbury area is assumed to have been similar to that in present-day orogenic regions. At a depth of 20 km, the temperature was in the range of 600° to 800°C (Uyeda and Horai 1964). The area was covered by a wedge of Huronian volcanic and sedimentary rocks and was under water (Figure 22.6a).
2. The impacting body was of asteroidal size (1 to 3 km) and travelled at a cosmic velocity. Dence (1972) estimated that such a body could have had a density of 3.5 and a velocity of 15 km/second. Because of its mass, it penetrated the atmosphere

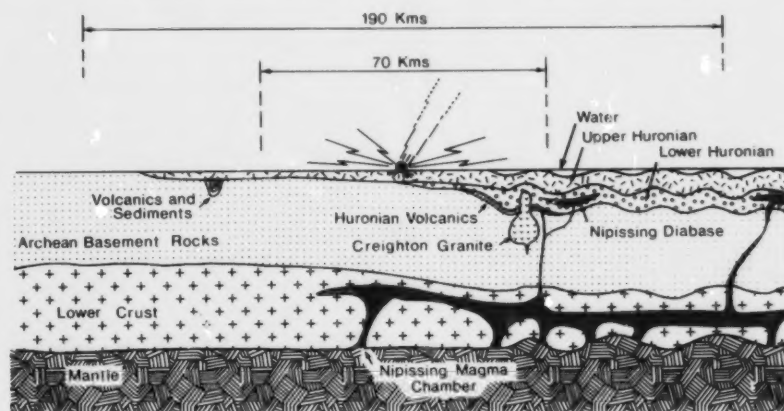
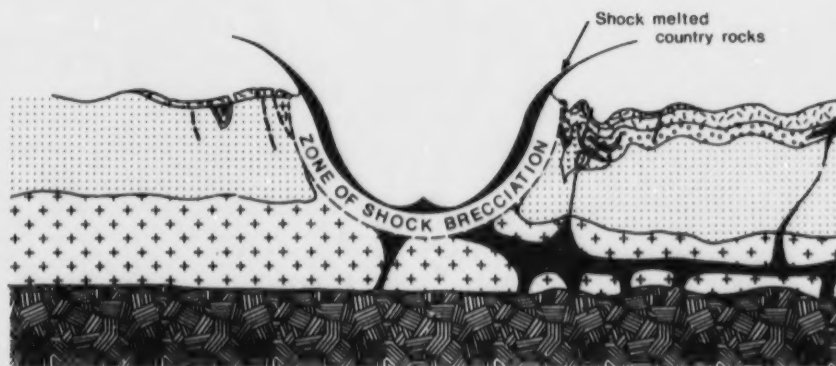
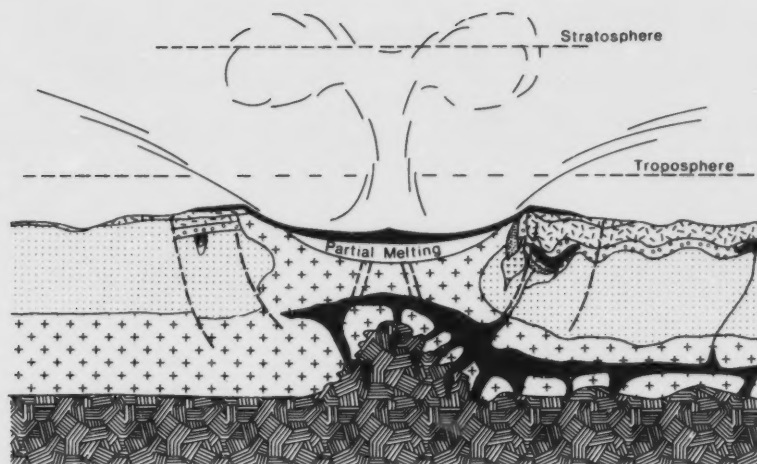


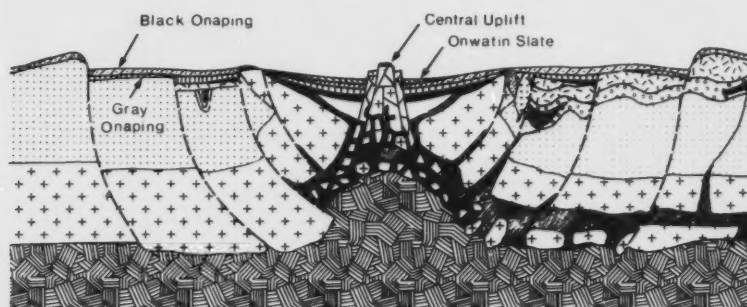
Figure 22.6a to 22.6e. Various stages of evolution of the Sudbury Structure.
22.6a. Regional setting



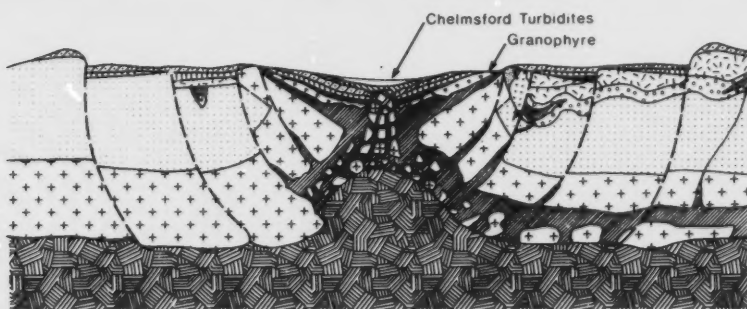
22.6b. Shock compression and excavation of the transient crater.



22.6c Ejection of melt, shocked, and brecciated country rock radially out of crater, followed by the elastic rebound and isostatic adjustments to form a modified crater.



22.6d Accumulation of fallback was followed by a tsunami-wave wash-in of fallback debris from outside the modified crater back into the crater. This was possibly also the time of upwelling in the central part of the modified crater giving rise to the central uplift. This was followed by emplacement of the noritic magma along the base of the modified crater, and erosion of the Onaping Formation to produce the Onwatin Formation mudstones. Collapse and adjustments continued producing a crater basin about 190 km in diameter.



22.6e Collapse of the magma chamber and central uplift resulted in the emplacement of the granophyre (a mixture of fractionated norite, impact melt, and molten country rock). Deposition of the Cheimford Formation turbidites was followed by the Penokean Orogeny and deformation of the Sudbury Structure into an elliptical shape.

without slowing down and hit the surface of the earth, releasing approximately 2×10^{30} ergs of total energy (French 1970).

3. The pressure generated at the point of impact was probably several megabars (French 1970). The resulting shock wave was transmitted to the target

rocks and back into the impacting bolide. This created a huge explosion.

4. Relaxation of extreme shock pressures caused vaporization of the upper layers of the country rock and part of the bolide.
5. Relaxation of intense shock pressures also caused melting of the target rocks (especially those in the lower parts of the crater) and the bolide which produced a lining of impact melt in the growing crater. Furthermore, as the shock wave dissipated, it caused intense shattering and milling of the country rocks, producing the Sudbury Breccias, and the peculiar conical fracture patterns known as shatter cones. The present authors estimate about 74 000 km³ of rock were affected by shock metamorphism and brecciation.
6. During the excavation of the transient crater, the impact melt and the shocked and unshocked, brecciated rock fragments were accelerated toward the crater wall and floor in a radial pattern and ejected out of the crater. Interaction between the impact melt and other components during ejection and their flight through the atmosphere could account for their present day inter-relationship.
7. Shortly after the impact, the ejected material began to fall back. Within 10 to 15 minutes, the bulk of the ejecta had been deposited to form a sheet of fallback material both inside and outside the crater (Figure 22.6d). The fine and very fine debris remained suspended in the atmosphere and stratosphere for a period of time ranging from days to years. Upon settling, it produced a thin, but extensive sheet of ash and pulverized rock. Although such a sheet is not recognized at present in the Sudbury area, this does not preclude its existence at one time.

The Gray Onaping Member is interpreted as the main fallback deposit, a roughly sorted accumulation of molten, fused, shocked, brecciated, and fractured country rock debris. The shard-like accumulation in the upper part of the member is interpreted as the fine tephra-like debris that took longer to fall back and, therefore, became fairly well sorted. Molten material in its flight through the atmosphere acquired aerodynamic shapes and became quenched. Upon deposition, the fragile material became fragmented. Quenching preserved the heterogeneity of the impact melt to produce fluidal glasses. The complex glasses and the country rock fragments have a continuous series of features that relate them to shock metamorphism.

The Basal Breccia of the Onaping Formation may represent either the earliest fallback, or a brecciated country rock mobilized along the crater floor or wall, with some material possibly contributed by slumping from the crater wall. Basal Breccia lenses in the Gray Onaping Member could have formed by slumping of breccia from the crater wall.

8. A tsunami-like wave carried fallback material from outside the crater and deposited it on the shaly upper part of the Gray Onaping Member, thereby producing the Black Onaping Member (or wash-in). The tidal effects produced fairly well developed bedding on a local scale. The carbonaceous matrix could have been incorporated outside the crater and brought in as part of the wash-in, or alternatively, it could have been generated by the impacting process.
9. The rapidly accumulating lithostatic load resulting from the fallback caused the underlying impact melt to force its way up along the crater wall and into irregular lenses and dike-like bodies in the fallback. Wherever the melt reached the depositional surface, it overflowed producing lava-like apophyses. Alternatively, the impact melt could have been flowing down the crater wall at the time when the fallback was creating a new depositional surface. In this latter case, the flowing action of the impact melt would be quicker and more consistent with the rapidly deposited character of the fallback. The lava-like impact melt could have been superheated, which could account for its apparently highly fluid character in spite of the abundant inclusions of shocked country rocks.
10. After the wash-in, reworking of the Onaping Formation produced the overlying mudstones of the Onwatin Formation.
11. The maximum diameter of the transient crater was probably larger than the present-day Sudbury Structure. Taking the present-day 35° dips of the Sudbury Structure on the North Range, and about 5 km of erosion, the authors estimate that the original modified crater had a diameter of about 70 km and an upturned collar (Figure 22.6b). According to Gault and Wedekind (1977), such a crater would be formed in about 70 seconds and would take about 2 minutes for the elastic rebound of the floor in a crater this size (Cooper and Sauer 1977) to produce a modified crater.
12. In response to the intense and major adjustments, the area peripheral to the modified crater collapsed to produce the Sudbury crater basin measuring about 190 km in diameter. A central uplift was formed in the modified crater in response to the elastic floor rebound and subsequent adjustments.
13. The collapse process (12) produced further intense milling of country rocks, giving rise to Sudbury Breccias with flow banding. This resulted in zones of intense brecciation some distance from the modified crater.
14. Excavation of the crater and subsequent rebound and isostatic adjustments created unstable conditions in the lower part of the crust and mantle. As

a result, basic magma rose from depth and intruded the modified crater and the impact crater basin, producing the Sudbury Igneous Complex and its Ni-Cu sulphides. This was probably a long and complex magmatic cycle.

15. Collapse of the magma chamber steepened the crater walls, and in the same process, the central uplift of the modified crater collapsed.
16. Faulting further modified the Sudbury Igneous Complex.
17. Deformation of the impact crater by the Penokean Orogeny followed. The South Range was compressed and dislocations along faults occurred.
18. Deposition of the Chelmsford Formation turbidites in a deformed impact crater was followed by minor deformation in the late stages of the Penokean Orogeny.
19. The Wanapitei Lake impact crater (37 Ma) was superimposed on the Sudbury impact structure and deformed it on the East Range.
20. Erosion of the Sudbury Structure occurred to its present level.

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CHAPTER 23

Morphological Features of the Sudbury Structure in Relation to an Impact Origin

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ABSTRACT

The Sudbury Structure is considered by many geologists to be a highly eroded and modified impact crater. This opinion is based on the presence of various features that are correlated with those of known meteorite impact craters. These features are identified as shock metamorphism of minerals, shatter cones, and the voluminous amounts of breccia that are present both within the Sudbury Structure and its Footwall. Additional evidence is found in the morphology of the Sudbury Structure. Large fresh lunar craters have a polygonal outline which controls the position of large troughs distributed around the crater wall. The Sudbury Structure has large troughs whose positions can be used to deduce an original polygonal outline. The large lunar craters have terraces along a gently sloping crater wall. The Sudbury Structure has terraces along its walls, and the position of the massive sulphides within these terraces, along with paleomagnetic data, indicate an originally shallow angle of repose (5° to 20°) for the walls of the Sudbury Structure. The shock-metamorphic evidence indicates that the Sudbury Structure has an impact origin; the morphological features strengthen this view.

INTRODUCTION

Volcanic models have traditionally been proved to explain the nature and origin of the Sudbury Structure (Thompson 1957). Evidence has been found, however, which relates it to meteorite impact (Dietz 1964; Guy-Bray 1966; French 1967; Peredery 1972). This evidence includes:

1. shatter cones in close association with the Sudbury Structure
2. shock-metamorphic effects within the minerals that make up the target lithologies
3. the extraordinary and voluminous amounts of breccia that are present both inside the Sudbury Structure (the Onaping Formation) and within its wall rocks (the Sudbury Breccias)

In considering the meteorite impact hypothesis for the Sudbury Structure, it is necessary to determine if the Structure has morphological characteristics typical of known large impact craters.

Lunar craters have been the focal point for the work on crater morphology and they, along with complementary studies on terrestrial craters, have lead to a general understanding of the processes associated with impact cratering. The characteristics of these craters that have been established by Head (1977) include: a flat floor with central peak or central peak ring, a polygonal outline with terraces along the crater wall, and a crater wall slope of $< 20^{\circ}$.

If the Sudbury Structure was formed by meteorite impact, it should exhibit characteristics similar to those above. Unfortunately, data for the deep, central parts of the Structure are practically non-existent, so that the presence of a flat floor and central peak cannot be determined.

It is, however, possible to compare the other characteristics of large lunar impact craters with those of the Sudbury Structure. Before attempting this, the dominant features of lunar impact craters will be reviewed.

LUNAR IMPACT CRATER CHARACTERISTICS

The Polygonal Outline

A selenographic map of the west part of the near side of the moon (Photo 23.1) shows the dominant features of the crater Copernicus. The terracing of the crater wall, the flat floor, the central peak, and polygonal outline are well illustrated.

Well developed troughs are present at the vertices of the polygon (*see* Photo 23.1). As the angles between adjacent troughs are commonly very nearly multiples of 15° (Photo 23.1), the crater exhibits geometric regularity.

It is suggested that during the excavation of the crater, much of the ejected material was blown out at the trough locations, and that the troughs acted as channel-ways to direct the ejected material outward, resulting in the formation of "rays" of ejecta material. If this suggestion is correct, the rays should show the same geometric regularity as the troughs.

The crater Kepler has particularly well developed rays. Their angular relationship is illustrated in Photo 23.2, in which it will be seen that the rays form angles that are multiples of 15° . The rays of the crater Kepler are in accordance with the observations for the crater Copernicus, and they suggest that regular, geometric polygonality may not be a feature restricted to the crater Copernicus, but may be common to all large, rayed craters. The craters Mena on Mercury, and Aristarchus and Tycho on the Moon are good examples of other craters that show the same patterns.

Crater Wall Slope

Examination of depth/diameter ratios for lunar impact craters reveals that the linear increase depth with diameter ceases with diameters in excess of 15 km; thus very few craters exceed 5 km in depth (Head 1977). Immediately after excavation of the transient crater, the depth/diameter ratio is about 0.2. With this ratio, the average internal wall slope is 22° (Melosh 1977). The larger craters, however, undergo modification by the



Photo 23.1. Selenographic map of the crater Copernicus showing its major morphological features. The geometric relationship of its polygonal shape has been added. Chart courtesy of the Aeronautical Chart and Information Center of the U.S.A.F.

slumping of the crater rim; this process can produce crater walls with slope angles that are $< 22^\circ$.

Terraces

The terraces that are present along the walls of large lunar impact craters (Photo 23.1) are the result of slumping of the highly brecciated and mobile crater walls. Details of the wall of the crater Copernicus are shown in Photo 23.3. Slump terraces are discontinuous features with only limited lateral extent. The sun's rays have a low incidence angle in Photo 23.3, with the result that the shadow which the sun casts upon the back of the slump terraces indicates that the radially arranged inner edges of the terraces are higher than the outer edges.

THE SUDBURY STRUCTURE

The Polygonal Outline

It can be seen from the geological map (Figure 23.1) that the Sudbury Structure is not now polygonal. It has

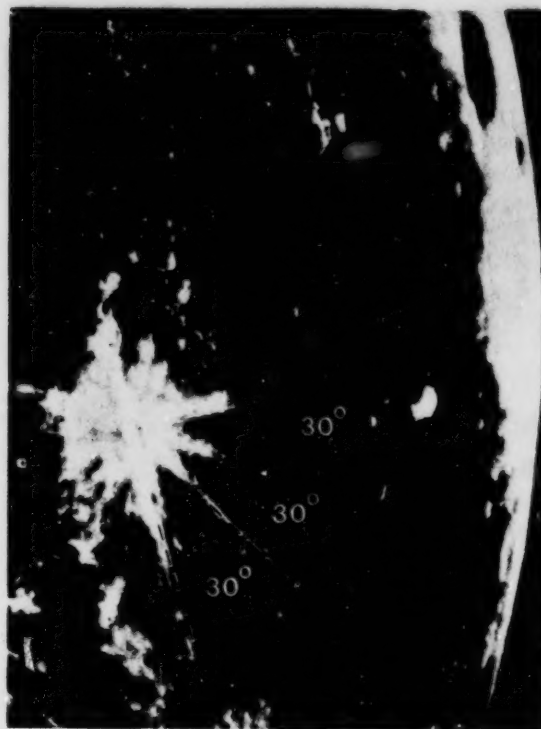


Photo 23.2. View of the moon showing the crater Kepler and its well-developed ejecta. Photo courtesy of Lunar and Planetary Institute.

undergone considerable deformation. If a reconstruction of the shape of the Sudbury Structure is attempted, a morphological feature is common to both the Structure and the large lunar impact craters can be discerned. This common feature is the presence of troughs.

The troughs within the Sudbury Structure, which are filled with sulphide-bearing Sublayer rocks (Souck, Podolsky *et al.* 1969), have been delineated by exploration drilling and mining operations. One such trough is at Levack (Figure 23.2) which hosts the Levack-Onaping mineralization.

A possible original outline of the Sudbury Structure can be reconstructed by drawing a circle with the same circumference as the present outer rim of the Sudbury Igneous Complex. This assumes that the contact of the Sudbury Igneous Complex delineates the crater wall position. The elevation point of the presently visible crater wall, within the original impact crater, is unknown. By using an arbitrary reference point, the Sandcherry Creek Fault, the approximate position of all the known significant mineral occurrences can be plotted on the rim of the circle. Most of the known mineral deposits are related to the troughs. Some of the deposits, notably those in the eastern end



Photo 23.3. Photo of the wall of the crater Copernicus on the moon showing well-developed terraces. Due to the low sun angle the inner edges of the terraces cast deep shadows across the back edges of the terraces. Photo courtesy of Lunar and Planetary Institute.

of the Sudbury Structure, occur in deformed terrain, and their association with an obvious trough structure is inconclusive. However, if it is assumed that most ore deposits are related to troughs and if these troughs are plotted on Figure 23.3, an analogy can be seen between these and the vertices of the polygonal shape of some large impact craters. It is proposed that these approximate the original polygonal shape of the Sudbury Structure. It is interesting to note that the radial offset dikes, which are an integral part of the Sudbury Structure, are all associated with one or another of the troughs.

From the reconstruction in Figure 23.3, it can be seen that the angles between the centres of adjacent troughs are approximate multiples of 15° . It is suggested, therefore, that the Sudbury troughs are megastuctures that are equivalent to those observed in lunar impact craters.

As the inter-trough areas are either barren or nearly so, it is also suggested that the Sudbury troughs determined the geographical locations of the ores.

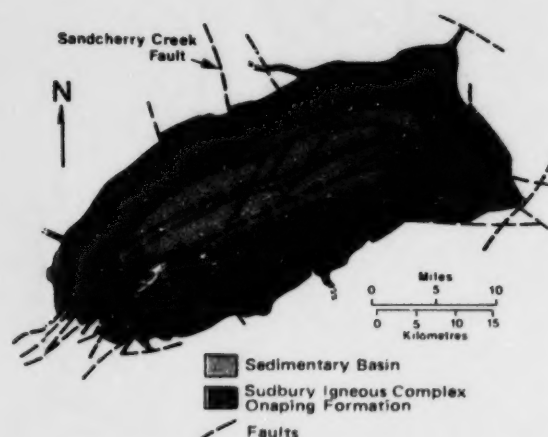


Figure 23.1. Generalized map of the Sudbury Structure with its associated faulting.

Other terrestrial impact craters exhibit a polygonal outline similar to that proposed for the Sudbury Structure. For example, the geological map of the Manicouagan crater show the crater's polygonal outline to be delineated by the surrounding lakes and rivers (Figure 23.4). The angle between adjacent vertices of the polygon are multiples of 15° as in the case of the lunar crater Copernicus and the Sudbury Structure. Another well documented crater is the Charlevoix astrobleme on the shores of the St. Lawrence River. Mapping by Rondot (1979) indicates a polygonal shape for this crater, with the angle between adjacent vertices being multiples of 15° (Figure 23.5).

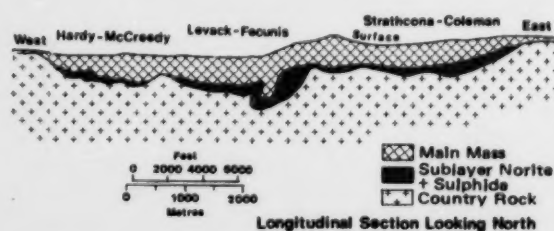


Figure 23.2 Longitudinal section through part of the Sudbury Igneous Complex showing the character of the Levack Trough.

Crater Depth and Slope of Crater Wall

Large impact craters have crater wall slopes averaging 22° or less. This contrasts with the present average dips of 45° for the north rim, and the steep to vertical dips of the south rim of the Sudbury Structure. It must be emphasized, however, that the Sudbury Structure has been endogenically modified by the post-impact intrusion of a magma within the crater. Endogenically

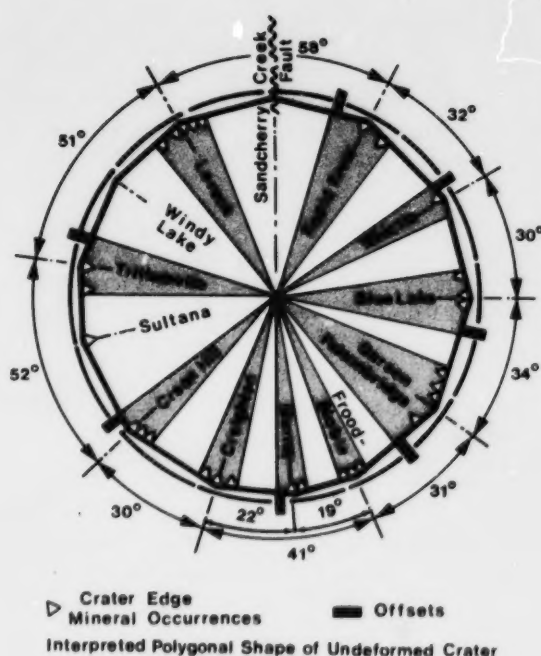


Figure 23.3. Interpreted polygonal shape of the underformed Sudbury Structure.

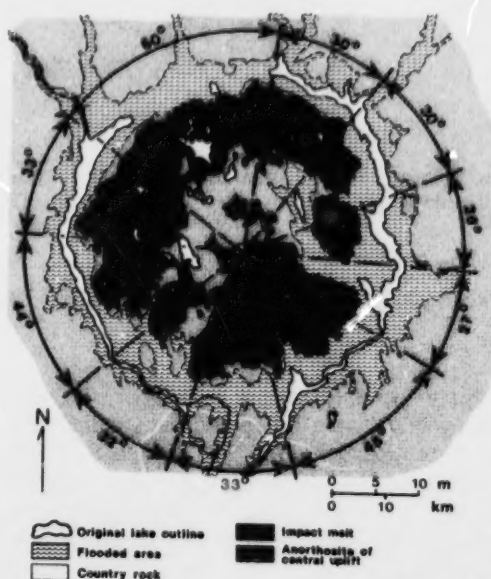


Figure 23.4. Generalized geological map of the Manicouagan crater, Quebec, Canada, showing the polygonal outline of the crater and its geometric pattern. Modified from map by Geological Survey of Canada. (Modified after Murtaugh 1974).

modified craters are quite common on the lunar surface and also on other planetary bodies (Shultz 1982).

At Sudbury, it appears that after the intrusion of the magma (the Sudbury Igneous Complex), the cen-

tral part of the crater underwent substantial subsidence, presumably caused by the collapse of the underlying magma chamber. Peredery and Naldrett (1975) suggested similar subsidence to account for the emplacement of the granophyre at Sudbury. Paleomagnetic work by Morris (1979) indicates that at the time of the intrusion of Sudbury Igneous Complex norite, the Sudbury Structure had the "form of an open syncline with the limbs dipping approximately 5° to 20° ". This is in good agreement with what would be expected for the original crater wall slope by analogy with lunar craters. According to Morris, this open syncline was subsequently deformed in such a way that "all limbs were dipping between 40° and 50° ". This symmetrical type of deformation was probably caused by subsidence of the crater.

The result of this subsidence is also reflected in the character of the sedimentary basin within the central part of the Sudbury Structure. Thomson (1957) described the Whitewater sediments as having been deposited in a basin of subsidence. The subsidence necessary to deform Morris' "open syncline" into one with limbs dipping between 40° to 50° would have had profound effects on any central uplift that may have been present. Accordingly, theoretical considerations of crater depth may no longer apply to the present-day Sudbury Structure.

Terraces

The Sudbury Structure Footwall rocks form a megabreccia with more intensely brecciated zones at its in-

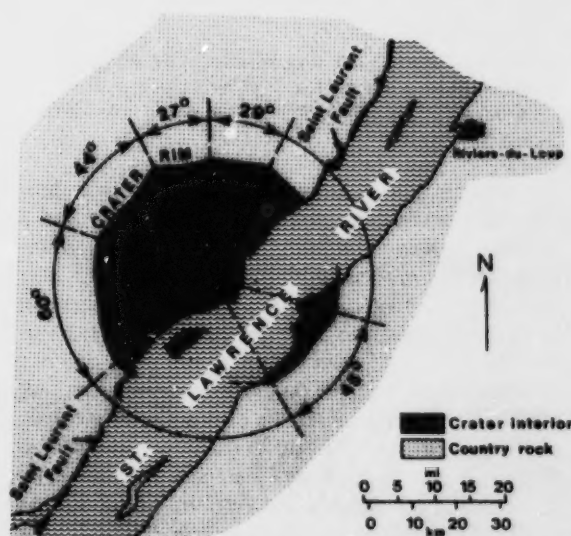


Figure 23.5. Geological map of the Charlevoix crater, Quebec, Canada. Modified from map by Jehan Rindot, Ministère des Richesses Naturelles du Québec (1979).

ner edge in contact with the norite body (Pattison 1978). This megabreccia can extend hundreds of m away from the norite contact and is characterized by very large blocks (10s of m) of various lithologies closely packed together with variable but generally minor amounts of matrix separating them. The matrix is variable in texture as well as composition and is commonly known as Sudbury Breccia (Speers 1957).

Many of the orebodies at Sudbury are located in what has traditionally been referred to as "embayments". These "embayments" are structures which recur vertically at irregular intervals along the norite contact, and they cradle Sublayer material which is commonly the host for the mineralization. In terms of crater morphology, these embayments can be interpreted as slump terraces which occur along the crater wall. Figure 23.6 is a schematic model which illustrates the nature of embayment structures in relation to slump terraces.

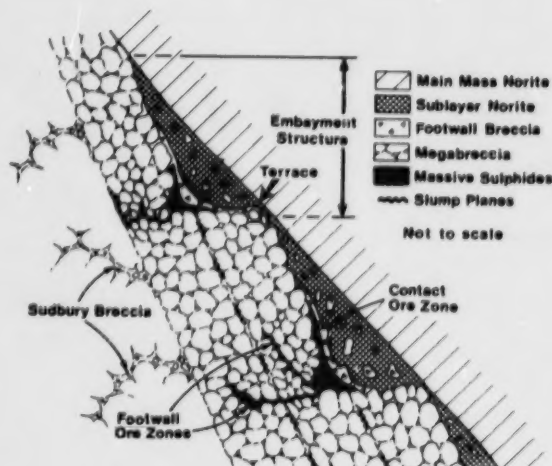


Figure 23.6. Diagrammatic representation of the slump terraces that are present along the walls of the Sudbury crater. Those terraces that are within the trough environments are often heavily mineralized.

Examination of known orebodies serves to illustrate this terrace concept. The Levack Mine Number 4 orebody is shown in Figure 23.7. The wall rocks surrounding this orebody are a megabreccia. Also, note the lack of sulphides on the flat floor of the embayment in its present position. However, as emphasized earlier, the present 45° dip of the contact is not the one which was present at the time of deposition of the sulphides. By rotating the section back to the original angle (approximately 20°) of repose of the crater wall (Figure 23.8), the sulphides assume a gravitationally stable position within the lowest point of the embayment. The same observations are true for the Levack Number 1 orebody as seen in Figure 23.9. Of particular interest is the distinctive shape of the embayment which corresponds very well with the shape of the

slump terraces of lunar craters. All of the major contact orebodies within the Levack trough can be shown to have these terrace characteristics. Numerous other terraces have been delineated in various parts of the Sudbury Structure. However, only those terraces that occur within trough environments are known to contain ore.

Within the Sudbury Basin, the troughs are the major structures which control the distribution of the ores, and it is normally the terraces within these troughs which are the specific locations of the ores.

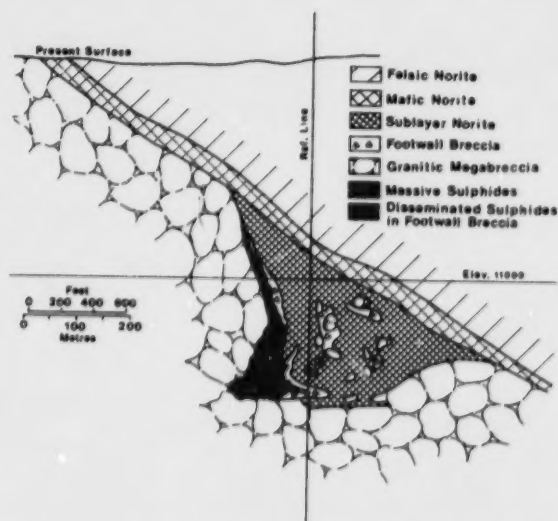


Figure 23.7. Section through the Levack Number 4 orebody showing the well-defined terrace.

DISCUSSION

The morphological features of the Sudbury Structure are analogous to those of large impact craters on the moon. These features support the view that the Sudbury Structure resulted from a meteorite impact. The comparative lists of the characteristics of large impact craters and of the Sudbury Structure that follow make this apparent.

Large impact crater characteristics:

- shatter cones
- shock metamorphism of minerals
- impact breccias
- polygonal outline believed to control the position of large troughs distributed around the crater wall
- gentle crater wall slope
- terraces along the crater wall
- central uplift

Sudbury Structure characteristics:

- shatter cones
- shock metamorphism of minerals
- impact breccias (Onaping Formation and pseudotachylites)
- a polygonal shape can be deduced from the position of large troughs distributed around the Sudbury Structure walls
- original gentle wall slope indicated by paleomagnetism
- the embayments that host the sulphides can be interpreted as terraces

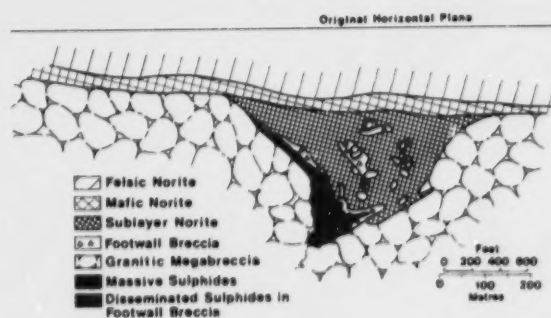


Figure 23.8. Section through the Levack Number 4 orebody rotated back to gently sloping position of crater wall at time of crater formation. The sulphide ores take on a gravitationally low position within the terrace indicating that they were probably deposited at a time when the crater wall was still in its original position.

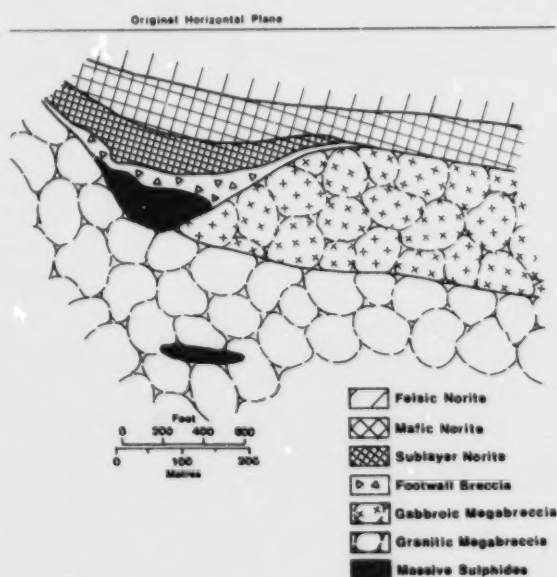


Figure 23.9. Section through the Levack Number 2 orebody which has been rotated in the same manner as Figure 23.8.

—no conclusive data available for presence or absence of a central uplift

The morphological features of the Sudbury Structure are what would be predicted if it were formed as a result of meteorite impact. Furthermore, the "meteorite impact hypothesis" for the origin of the Sudbury Structure can be used to develop a model for the formation of the Sudbury ore deposit, which in turn can be used as an aid in exploration.

ACKNOWLEDGMENTS

The author wishes to thank all those members of the Inco Limited geological staff who, over the years, have helped in the formulating of the ideas expressed in this paper.

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SUGGESTIONS AND SYNTHESIS

CHAPTER 24

Sudbury Problems and Suggestions for Further Research

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ABSTRACT

Relevant to the Sudbury Structure, further research is suggested on the distribution of the high metamorphic rank Levack Gneiss Complex, on the thermal aureole in the Footwall of the Sudbury Igneous Complex, on the distribution and orientation of shatter cones, and on the controversial Onaping Formation. Is the Onaping fall-back the result of meteorite impact or is it a pyroclastic deposit, possibly of ash-flow origin?

Problem areas in the Whitewater Group include the origin of carbon in the Onaping and Onwatin Formations, of the fragmental sulphides in the Onaping Formation, and the provenance of the Whitewater rocks and their time equivalence with other Early Proterozoic rocks.

Geologists are still debating the petrology and time relationships of the several components of the Sudbury Igneous Complex. Is the Complex a simple differentiated unit or does it represent 2 separately differentiated and separately intruded units? How has assimilation of siliceous material, quartzite breccia by

the granophyre, footwall granitic rocks and quartzite by the norite, affected the petrology of these rocks? The components of the Sudbury Igneous Complex sublayer, namely the contact, embayment, and offset rocks and the controversial Footwall Breccia, still require further work on resolving the petrographic radiometric age problems.

The following studies of the geochemistry of the Sudbury Igneous Complex are underway, but further research is warranted on them: variations of SiO₂ content, REE enrichment patterns, Eu anomalies, Sr isotopic ratios, refined zircon ages, structural states of feldspars, the provenance of PGEs, and partition coefficients between sulphide and silicate melts.

Still unresolved is why there is so much more ore in the South Range than in the North Range, and here, why in only the short 8.2 km Onaping-Levack segment? Would the controversial uplift of the South Range in respect to the North Range be part of the answer, and would more study of the South Range mylonite zones help the uncertainty as to the amount of uplift?

The recent discovery by geophysics of a 3 km thick magnetic mafic-ultramafic still at a depth of 6 km may not only help resolve the South Range gravity high problem, but may also resolve the origin of the ultramafic xenoliths in the norite and may even provide a non-meteoritic cause of shock metamorphism. Further research is needed here. As a help, perhaps the long-asked-for deep hole in the Basin could be over this body.

More data are needed to firm up the concepts of the proposed multiplicity of Sudbury Igneous Complex events that recent paleomagnetic studies have found.

INTRODUCTION

As in all other geological research, Sudbury research is a continuing process, and has been going on for a long while at Sudbury. W.H. Collins, former Director of the Geological Survey of Canada and one of the pioneers of Sudbury geology, put it very well when he (Collins 1934, p. 134) said in the first of his Royal Society of Canada series of 4 papers on Sudbury: "The Sudbury Nickel Irruptive furnishes a most interesting case of the painfully slow, caterpillar-like, yet logical way in which we grope our way to an understanding of big and intricate geological bodies."

In his discussions of problems in Sudbury geology and suggestions for further research, the author will begin with the oldest rocks, those in the Footwall, and then proceed to younger rocks, the ores, and other subjects of interest and concern.

FOOTWALL

The variability in the types and competencies of the immediate Footwall rocks has resulted in an irregular distribution of structurally dependent features around the Sudbury Igneous Complex. More detail on the rock types of the Footwall is needed. Detailed mapping has been done and is being done in selected areas by Inco Limited, Falconbridge Limited, and the Ontario Geological Survey. Additional mapping on 1:2400 scale with complete outcrop coverage, extending for at least 3 km into the basement rocks right around the Sudbury Igneous Complex would elucidate the nature and development of these rocks. Detailed information on the distribution, petrography, geochemistry, and structures of the immediate Footwall rocks, would enable a better evaluation of the effects of these parameters on the distribution of contact, embayment, and offset ores. This detail would also provide an opportunity to study the effects of the 2 or more regional metamorphic events in the vicinity of the Complex and would help to delineate the thermal metamorphic aureole of the Sudbury Igneous Complex itself. More informa-

tion is needed to extend the isograds delineated by Card (1964, 1978) west of, and at the southwestern corner of the Sudbury Igneous Complex.

More study is needed of the granulite facies rocks detected in the Levack Gneiss Complex to determine how its distribution is related to the Sudbury Igneous Complex, and to what extent the same history of uplift exists as is suggested by Card *et al.* (Chapter 2, this volume) for the granulite facies terrain in the Kapuskasing Structure. These studies, combined with further detailed structural investigations may help to decide whether or not the Sudbury Structure was domal or anticlinal. Some authors say it was domal (Card *et al.*, Chapter 2, this volume), others see no evidence of it (Dressler, this volume). The studies may also contribute to explaining the problem raised by Rousell (Chapter 5, this volume) of the large east end embayment of the Sudbury Basin.

Further structural studies in basement rocks could include investigation on the ground of the zone of ring fractures outside the Sudbury Basin that Dressler (Chapter 6, this volume) deduced from a study of Landsat satellite images and on which he recommended further work.

Features of the Footwall are closely related to the morphology of the Sudbury Basin. Several geologists, most recently Morrison (Chapter 23, this volume), have studied comparisons between morphological features of the Sudbury Structure and features of lunar impact craters as seen on photographs of the moon and derived selenographic maps. No doubt this interesting work will be continued.

Sudbury Breccia

The Sudbury Breccia is a Footwall feature about whose distribution not enough is known and about whose origin there is still lack of consensus. This is despite much previous work and the recent very comprehensive work of Dressler (Chapter 6, this volume). The author feels that considerable clarification about the breccia would come about if we reverted to the geographically-oriented nomenclature originally used for Sudbury area breccias.

Early in the development of geological concepts at Sudbury, geologists referred to Frood Breccia in the Frood-Stobie area of the South Range. With further work, the term, Frood Breccia, was expanded to include all similar breccia in the Footwall in the South Range east and west of Frood, and it became generally known as the Sudbury Breccia. At a still later date, the term, Sudbury Breccia, came to include the North Range Levack breccia, a breccia different in many ways, particularly in its lack of metamorphism, from the original Frood Breccia. In recent years, somewhat similar breccias as far as Espanola, which is located 30

km west of the western end of Sudbury, have been referred to as Sudbury Breccia. This is close to the outer limit of the 9 to 40 km width of Footwall defined by Dressler (Chapter 6, this volume).

Extrapolation and correlation of breccias is a much more risky exercise than doing the same for rock units. If a reassessment of the Sudbury area breccias were made in terms of the originally identified, less extensive units, using a revised survey of their distribution and age relations, much would be added to our understanding of their origin and relevance to the Sudbury Structure.

A further problem concerning the Sudbury Breccia raised by Dressler (Chapter 6, this volume) is its classification as a breccia similar in kind and origin to the pseudotachylites at Vredefort and Manicouagan. This reflects on the problem of the origin of the Sudbury Structure; is it exogenic or endogenic?

Footwall or Granite Breccia

Considerable lack of consensus still exists about the distribution and age relations of one of Dressler's Footwall Breccia, this despite all the earlier work and despite Dressler's own very detailed work (Dressler, Chapter 6, this volume). To some extent, particularly in reference to the North Range geology, Dressler's Footwall Breccia would appear to be the North Range leucocratic breccia of Souch, Podolsky *et al.* (1969) and of Pattison (1979). Early in the history of geological studies at Sudbury, this breccia was referred to as either Levack granite breccia or Levack granite breccia matrix, to distinguish it from a somewhat similar breccia, Waddell Lake breccia, in the East Range. In recent years, there has been a tendency not only to group these North Range breccias together, but also to identify them with occasionally occurring, somewhat similar, breccias in the South Range. Because of the differences between North Range and South Range Sudbury Structure geology, such grouping has led to the present lack of consensus, particularly in age relations, concerning these breccias.

Further study of these Footwall Breccias, having in mind the differences that led to the original nomenclature, would lead to greater understanding of their part in the history not only of the Sudbury Igneous Complex, but also of the Sudbury Structure. Dressler's (Chapter 6, this volume) remark that the Footwall Breccia...besides the rocks of the Onaping Formation is the most puzzling rock in the Sudbury area...emphasizes that further study of this breccia is still needed.

Shatter Cones

The discovery of shatter cones at Sudbury started the debate on the possibility of a meteoritic impact origin

for the Sudbury Structure. Shatter cones do exist at Sudbury, but there is still some doubt about their relevance as proof of the meteoritic impact. It has been 18 years since Guy-Bray (Guy-Bray and Geological Staff 1966) did the first mapping and made the first orientation studies on shatter cones around the Sudbury Basin. Since then, many scattered observations have been made both here and elsewhere. Perhaps, it is time at Sudbury for a more extensive mapping of their distribution and for further detailed studies of their orientations (T.L. Muir, Geologist, Ontario Geological Survey, personal communications, 1983). This could lead to a reassessment of their relevance to the origin of the Sudbury structure, meteoritic, or otherwise.

WHITEWATER GROUP

Onaping Formation

The origin of the Onaping Formation, meteoritic or volcanogenic, as suggested by Guy-Bray (1972, p. 1) is "central to the Sudbury controversy". This controversy is likely to go on for some time, and the proponents for each side will undoubtedly continue to seek evidence in support of their views. The systematic detailed mapping program of the Onaping Formation by the Ontario Geological Survey is coming up with solutions to the problem that may well prove to be acceptable.

The most comprehensive recent work, principally in the North Range, is that by Muir (1981, 1982, 1983) and by Muir and Peredery (Chapter 7, this volume). In spite of the mapping and the petrographical and petrochemical work done by Muir, and the very large number of new chemical analyses, Muir feels constrained to say that not all the unusual features in the rocks are as yet explained.

The author feels that the petrography of the principal members of the Onaping Formation, the Grey and Black Members, exhibit rather convincingly, a volcanic pyroclastic derivation, and specifically an ash-flow origin. Those geologists in favour of a fall-back (meteoritic) origin for much of this material use, as a supporting argument, similarity of much of the Onaping Formation to suevite, the fall-back component of the Ries crater assemblage of rocks. It would, therefore, be helpful to have someone make and publish detailed petrographic and, in particular, textural comparative studies of the Ries suevite and the Onaping rocks.

The external relations of the Onaping Formation may hold clues to its origin and these may best be found by further careful study of its lower and upper contact areas.

In the lower contact area, the Basal Member, a quartzite breccia having an igneous matrix immediately above *bona fide* granophyre, is still a problem.

Hawley (1962, p.20-21) has said "The quartzite and quartzite breccia at the base of the Onaping volcanics introduces a complication which cannot be settled until its age can be determined."

The lower contact area is also the interface between the Onaping Formation and granophyre. Are these rocks vastly different in age or are they approximately coeval and magmatically related, as suggested by Stevenson (1983)? Can the relationship be determined by way of the bodies of trachytic and dacitic lavas and dikes found in the Onaping Formation? This particular interface area could have relevant data, but further research is needed.

Another problem in the lower part of the Onaping Formation is to explain the extensive recrystallization and modification of the original texture of the Grey Member. Is this the result of thermal metamorphism by the granophyre, as suggested by early workers and later considerably amplified by Chute (1937)?

The origin of widespread sulphide, principally pyrrhotite, with minor chalcopyrite, and pentlandite throughout the Onaping Formation is unresolved. The sulphide minerals occur principally as fragments, and about their origin, Rousell (Chapter 9, this volume) says that "sulphide-rich material must have been present prior to brecciation and incorporation in the unit". However, the author feels that the sulphide fragments represent coeval volcanogenic hydrothermal sulphide replacement of indigenous pumiceous lapilli. These are different concepts about a major feature of the Onaping Formation, and obviously more work is required to reconcile them.

Onwatin (including Vermilion Member) and Chelmsford Formations

In the upper contact area of the Onaping Formation transitions into the Vermilion carbonate member of the Onwatin Formation or, where that is missing, into the Onwatin slates occur. Here, exist problems related to the origin of cherts and the peculiar algal-like structures in the Vermilion Member, and problems related to the origin of the probably exhalative sulphide minerals of the Errington and Vermilion Mines. Studies here may also throw light on the widespread distribution of the sulphide minerals found throughout the Onaping Formation. In areas of this upper contact, where the Vermilion Member is very thin or missing, the passage of the Onaping Formation into Onwatin Formation is characterized by laminae of tuff or tuff-like rock in laminated Onwatin mudstone; this volcanic aspect of the Onaping-Onwatin transition requires further study.

As has been suggested by A.D. Mutch (consulting geologist, personal communication, 1984), a parallel study defining in detail the distribution of carbon

in the Basin rocks would be rewarding. Is the source of this carbon deep within the crust or is it mostly of organic origin?

Further, in respect to the Onwatin and Chelmsford Formations, Rousell (Chapter 8, this volume) is concerned that type sections for these formations have not as yet been defined. The provenance of these formations, whether from the Onaping Formation or from the basement craton, is still in doubt. There continues to be speculation about the time equivalence or not of the Whitewater rocks, particularly the Onwatin and Chelmsford Formations, with other Early Proterozoic rocks in Michigan (Card *et al.*, Chapter 2, this volume).

The author feels that if ever the Vermilion and Errington shafts are pumped out, every attempt should be made to get underground and study and report on the exposures there of the Onaping rocks, the Vermilion limestone, and the Onwatin slate. This would update and modify, in the light of current geologic and metallogenic concepts, the earlier underground studies of Thomson (1956).

SUDBURY IGNEOUS COMPLEX

Perhaps, more field and laboratory work has been done on the Sudbury Igneous Complex than any other geological unit in the Sudbury area. Mapping, collection, and careful studies of petrographic and petrochemical data are certainly underway by Inco Limited and Falconbridge Limited, by universities, and by the Ontario Geological Survey. The author can only indicate problem areas that he feels have priority in present-day research.

Granophyre

Field studies in the uppermost part of the granophyre, an area that includes its contact with and extension into the Onaping Formation, have not been particularly emphasized, perhaps because this area is remote from ore.

In this area, does the igneous matrix of the quartzite breccia at the base of the Onaping Formation form a continuum from the granophyre to such material as lapilli and shards in the Onaping Formation? How extensive has been the replacement of the quartzite of this breccia by the main body of the granophyre? Field evidence of this, particularly in the South Range, throughout and right to the bottom of the granophyre can be found. How important is it and what effect has the resultant silication of granophyre magma had on granophyre petrology?

Transition Zone

The transition zone between the lowermost part of the granophyre and the norite, earlier the intermediate

zone of Phemister (1932, p.2), and latterly, the Middle or Quartz Gabbro zone of recent workers (Naldrett and Hewins, Chapter 11, this volume), contains puzzling geology, much still unresolved, and requires further detailed mapping, and detailed petrographic and petrochemical study. Here, we may be able to solve the problem of whether the Sudbury Igneous Complex is a single differentiated unit or whether it represents 2 separately differentiated and separately intruded units. Is the one intrusive into the other? If so, what is the time interval between the two? Is it possible to detect an age difference by present-day refinements in radiometric techniques?

The transition zone in the South Range contains a very heterogeneous assemblage of rocks other than norite and granophyre, principally felsic dikes and large felsic inclusions. Their careful geological, petrographic, and petrochemical study would yield much needed information about the interface.

Felsites in and Adjacent to the South Range Norite

The author would like to suggest further study of the many felsite ("aplite") dikes and inclusions that are found in the main body of the South Range norite. In particular, more study is needed of those felsic dikes in the central part and at the eastern end of the South Range, and a determination should be made of their structural, petrographical, and geochronological relations, if any, to the Murray Granite. This is part of the problem of dikes extending into the norite from a granite that is supposed to be older. We also have the similar problem of age and origin of apophyses from the Creighton Granite into the norite at the western end of the South Range.

The whole South Range norite is full of felsitic inclusions and felsic dikes, but this is certainly not true of the North Range norite. Why is this? Is it because the South Range norite is much lower or deeper in Sudbury Igneous Complex stratigraphy than the North Range?

Sublayer

The lowermost norite, the breccias closely associated with the norite, and the offsets dikes (see Grant and Bite, Chapter 11, this volume), all 3 of which comprise the Sublayer, still present problems and should be mapped in considerable detail, not just locally, but completely around the Complex. It is realized that much has been done by Inco Limited and Falconbridge Limited, and local mapping has recently been an important part of the Ontario Geological Survey detailed mapping program. Nevertheless, the Sublayer and its components present a continuing major problem of characterization and interpretation. The Sublayer is closely related to the nickel-copper-platinum

group element ores and a correct understanding of all aspects of it is very important in exploration.

The Sublayer includes a heterogeneous assemblage of Sudbury Igneous Complex-related rocks, at the base of and temporally and spatially associated and varyingly similar to the Main Mass norite. It is not part of the Footwall complex. The Sublayer as understood, is seen to occur as disconnected lenses of Sudbury Igneous Complex-related breccia along the lower contact of the Complex, as the principal rock of the Complex in the several embayments that occur at intervals around the Complex, and as the quartz diorite of the offsets. Because of the considerable variability of these rocks and their widespread occurrence, the Sublayer can hardly be described simply, or in terms of an all-inclusive terminology. The author feels that this is the reason such a lack of consensus exists about the age relations and origin of the Sublayer. We do need more studies here, but studies with a greater appreciation of the great variety of the rock types involved are required. We need a separate delineation of these rock types by mapping and by petrographic and geochemical investigations. This aspect of the Sublayer is alluded to partly in Naldrett's comment (Chapters 11 and 25, this volume): "In our opinion, further work is required to define the distinction between the Contact Sublayer and marginal phases of the Main Mass norite on the South Range."

Complementary to such studies should be investigations of whether or not any of the Sublayer breccias can be identified with any of the breccia in the Onaping Formation. There is a considerable similarity in hand specimens, at least, between what the author termed in mapping, the Onaping "pink fragment, grey-green tuff" and pink phases of the Levack granite breccia matrix. The author feels they are different, certainly petrographically and in origin, but some think otherwise.

Quartz-Diorite Offsets

Quartz-diorite offsets constitute important components of the Sublayer. Grant and Bite (Chapter 12, this volume) and Cochrane (Chapter 15, this volume) have added very considerably to our knowledge, not only of the field relations and petrography, but also the whole rock geochemistry. Understandably, a few problem areas are indicated. These include the problems of the genetic relation of the offsets to the Main Mass norite, the problem of the enigmatic MacLennan Offset, the problems of the somewhat distant Manchester Offsets, and the problem of the chemically aberrant distal part of the Copper Cliff Offset south of Kelley Lake (Grant and Bite, Chapter 12, this volume). Other problems that could be explored include: the suggested relationship (Grant and Bite, Chapter 12, this volume) between the quartz diorite and the quartz diabase (trap) dikes found cutting the Sudbury Igneous Complex in the South Range; and the genetic relation suggested by

geochemistry between the quartz diorite and quartz gabbro of the Sudbury Igneous Complex (Grant and Bite, Chapter 12, this volume). Dressler suggests obtaining radiometric dates on the trap dikes found in the Whitewater Group.

Laboratory Research on the Sudbury Igneous Complex

Much of the laboratory research to date has been on the petrography and mineralogy of the Main Mass, most recently reported by Naldrett and Hewins (Chapter 10, this volume). One of the most recent advances in mineralogical investigations has been a study on the structural states of the Sudbury Igneous Complex feldspars (Schandl 1982; Schandl *et al.* 1982).

Recent advances in the field of rapid chemical analysis and the much greater availability of new whole rock analyses, have made for an updated and more thorough understanding of the whole rock geochemistry of both the Sudbury Igneous Complex and the Onaping Formation. Even though new interpretations of the geochemistry of the Sudbury Igneous Complex are continually forthcoming, they do not appear to be final. For example, a need exists for further study of the distribution of variations in the high SiO_2 content of much of the norite and most of the granophyre in order to help resolve the debate about the relative effects of extreme fractionation or of abundant assimilation of silica-rich rocks in the formation of not only the granophyre, but also of much of the norite.

Pertaining to Rare Earth Elements (REE), we need a more effective sampling grid in both the North Range and the South Range, with careful attention to the detailed geology of the environment from which specimens are selected in order to evaluate more accurately the significance of REE enrichment patterns and Eu anomalies. The same basic concept of sampling also applies very definitely to studies of the Sr isotopic ratios of samples of Main Mass norite and granophyre in evaluating absolute ages, and of age differences within the Sudbury Igneous Complex. Studies of variations in oxygen isotopic compositions are just starting, and more sampling traverses are needed to firm up interpretations related to assimilation by the Sudbury Igneous Complex, not only of the Onaping Formation but also of the Footwall gneisses. No doubt, trace-element geochemists working on the Sudbury Igneous Complex will soon turn to samarium-neodymium, which McBirney (1983) has described as "the most important new tool of the decade".

A problem that the author does not think has been sufficiently addressed in respect of Sudbury Igneous Complex geology is that of metasomatism. Evidence exists of widespread replacement albitization; it is limited to the norite, but is extensive in the granophyre and in the overlying quartzite breccia. Albitization is

also a feature not only of the norite and granophyre, but also of the Onaping Formation (Schandl 1982; Schandl *et al.* 1982). It is also generally known that potash metasomatism, principally microclinitization, is a feature of the lower part of the granophyre, and metasomatic orthoclase has recently been mentioned as a feature of the Black Member of the Onaping Formation (Schandl 1982; Schandl *et al.* 1982).

There is still considerable uncertainty about the extent of the metasomatism in the Sudbury Igneous Complex, and certainly about the source or sources of the circulating solutions responsible, both in the Sudbury Igneous Complex and the Onaping Formation. This is an area of mineralogical and geochemical research at Sudbury that could be explored further.

Mineral Deposits

In respect to the ore deposits and their regional setting, Innes and Colvine (Chapter 3, this volume) very commendably stress that "they are component parts of the complete geological setting of any area" and that "they nevertheless constitute an integral part of the regional metallogenic setting and must also be considered in that context". Gupta *et al.* (Chapter 18, this volume) would concur with these concepts when they refer to Sudbury as only one of several gravity-magnetic anomalies in the 350 km belt extending from Elliot Lake through Sudbury to Temagami and Englehart. The author, therefore, feels that workers not only in the immediate environs of Sudbury, but farther afield, should be very conscious of these concepts and actively apply them in their interpretation of local and regional geology.

An extensive data base is fundamental to metallogenetic studies. There are needs here for a data base. For example, the data base of gabbro-related mineralization is reasonably extensive, but the data base of mineral occurrences related to the Huronian volcanic and sedimentary rocks needs to be amplified (Innes and Colvine, Chapter 3, this volume).

It would seem that inasmuch as a satisfactory metallogenetic model requires the analysis of a great deal of data, the use of computerization techniques, and relevant data analysis, would be the next step in metallogenetic studies at Sudbury and environs, from Elliot Lake to Englehart.

As far as the ores themselves are concerned, problems relative to the distribution and localization of the several ore types are being well handled by Inco Limited and Falconbridge Limited. Details of sulphide mineralogy and ore genesis are parts of the research programs of universities, in particular the University of Toronto.

Perhaps one of the greatest problems relating to the ores is that of the sorting out of those ore-associated breccias at the base of the Main Mass norite, along

the contact, in embayment structures, and in offsets. In the North Range, the association is principally with granite breccia, equivalent to Naldrett's Footwall breccia matrix, and with various inclusion breccias. In the South Range, the principal associations are with the Murray breccia (if the author may resort to old terms), and with the inclusion-bearing offset quartz diorite of Cochrane (Chapter 15, this volume). There is still considerable lack of consensus about the age relations and origins of these Sublayer components.

A continuing problem of North Range ore geology is why, in all the length of the North Range, we should find the only producing mines, those of the Onaping-Levack area, with their reserves in excess of 200 million tons (Geological Staff, Falconbridge Limited, Chapter 14, this volume) in only 1 short 8.2 km segment of that length. No one has come up with a good answer.

Despite the vast amount of mineralogical and geochemical work that has been done on the sulphide minerals and Platinum Group Elements (PGE), problems and needs still remain. Naldrett (Chapter 13, this volume) said: "clearly more work is required before the provenance of the Platinum Group Elements at Sudbury can be taken as completely solved." He furthermore noted that we lack precise knowledge of the partition coefficients of metals between sulphide and silicate melts to aid us in precise modelling of metal distributions.

The geological problems related to specific deposits are well known to the mines geological staffs and their solution is best left to these geologists. Certainly, the comprehensive papers by Cochrane (Chapter 15, this volume) on the deposits of the Copper Cliff Offset, by Davis *et al.* (Chapter 16, this volume) on Little Stobie, and by Falconbridge Limited Geological Staff (Chapter 17, this volume) on the Falconbridge and East Mines give a very good picture of these South Range deposits. However, concerning the North Range deposits, some problems might be mentioned that have been suggested by the Falconbridge Limited Geological Staff (Chapter 14, this volume) and some suggested by the author.

The unresolved questions about North Range deposits include

1. the problem of why do we have both ore-bearing granite breccia and extensive contact lengths of otherwise similar, but barren, granite breccia
2. the reason for the spatial relation of Levack (Sudbury-type) breccias to granite breccia and to ore bodies
3. the importance or otherwise of the structural control implied by the linearity of the Strathcona and Coleman veins
4. the problems of alteration halos and of mineral and metal zoning both in depth and horizontally. Study

of these problems will help resolve whether or not concepts of multiple source rocks and of multiple mineralization periods have to be entertained.

Faulting

The considerable amount of space devoted to faulting in the paper on the Falconbridge and East Mines (Geological Staff, Falconbridge Limited, this volume) indicates the importance of ore-related faulting at Sudbury. This importance holds for other South Range mines as well. Fault zones appear to have controlled the emplacement of sulphide minerals and, therefore, a knowledge of timing of the various faults and of sulphide injections is important, but, like the Falconbridge Limited geologists, we also need to know more about the origin of the fault-emplaced sulphide minerals prior to faulting.

Earlier studies of the more areally extensive faulting, faulting throughout the Sudbury Basin as a whole, have been largely geographic, but the tendency in more recent years has been to quantify the intensity of faulting and to reduce the numbers of faults mapped.

A field of research in faulting that should be expanded is that related to the mylonite zones; these are so extensively developed in the South Range granulite. Careful delineation of these mylonite zones and a quantitative study of the relative intensities of mylonitization and recrystallization in the different zones would help to assess the importance and perhaps relative displacements along the different zones. This would all help in assessing the amount of "stratigraphic" separation between the North and South Ranges.

The problem of why the tremendous differences between the North and South Range geology and between North and South Range ore deposits is paramount in Sudbury geology. These differences have been ascribed to a considerable uplift by faulting of the South Range with respect to the North Range. Not only is the amount of the uplift in debate, but also the existence of any real amount of uplift. However, mylonite zones are recognized worldwide, in the United States, Scotland, and New Zealand, for the great displacements along them. The South Range mylonite zones, their distribution, planes of shear, and planes of flattening within them need investigation.

Geophysics

GRAVITY STUDIES

Recent geophysical studies (Gupta, *et al.*, Chapter 18, this volume) indicate that the origin of the Sudbury gravity anomaly, a problem that has plagued Sudbury geologists for so long, is not due to the downward extension of the Sudbury Igneous Complex. The cause is rather to be found in a sill-like body of mafic-ultra-

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mafic rocks about 3 km thick at a depth of about 6 km. Is this a hidden layered sequence of which the Sudbury Igneous Complex constitutes an upper differentiated part, and which may presently be represented by the many xenoliths found in the lowermost norite? Could a deep borehole, as has been suggested by many, and most recently by Burkhard O. Dressler (Geologist, Ontario Geological Survey, personal communication, 1983) help solve the depth and petrology of this hidden mafic body?

Gupta *et al.*, (Chapter 18, this volume) has indicated some problems that have been raised by his geophysical studies. Briefly these are:

1. The width of the mafic-ultramafic layer; does it extend south to the Grenville Front?
2. The origin of the magnetite, necessary to produce the magnetism of this layer. If magnetite originated by serpentinization, there are problems of the source of the water, of space, and of pressure build-up. Also, would the release of such pressures by faulting and subsequent temperature generation be sufficient to produce the shock metamorphism that seems to be associated with the Sudbury Structure?
3. The problem of the small amount of room that is left by the Model Y (Gupta *et al.*, Chapter 18, this volume) for the rather thick sequence of Southern Province volcanic and metasedimentary rocks, and lastly
4. A major problem in paleotectonics posed by the origin of such large accumulations as the Elliot Lake-Englehart structure, of which Sudbury is a component part.

PALEOMAGNETISM

Paleomagnetic studies (Morris, this volume) indicate that the Sudbury Igneous Complex contains records of multiple intrusions (5 temporally distinct periods), of multiple deformation events (4), and of multiple mineralization events (3). It would appear that geological studies need to be undertaken that are directed to an understanding of this multiplicity of geological events.

One of the magnetic pulses called for by Morris (this volume) resulted in the emplacement of the much-neglected Onaping-Onwatin basic sills.

Morris (this volume) makes a plea for more radiometric data of identifiable phases of the granophyre and for more paleomagnetic studies of that granophyre in the southwestern corner of the Complex.

In interpreting the metamorphic evolution of the Sudbury Structure, Morris (this volume) points out that paleomagnetic studies can be very helpful. He adds, however, that only limited paleomagnetic data are available.

The author feels there is a need for further geological reassessment of the extent of the hydrothermal mi-

neralization that is indicated by one of Morris' pyrrhotite-residing magnetizations.

SUMMARY

The Ontario Bicentennial Project on Sudbury geology is unique in the long history of geological research at Sudbury. At no other time, as far as the author can recall, has a group of geologists taken detailed inventory of the work that has been done and is underway. Problems and deficiencies in our knowledge that became apparent will be of great help in determining priorities and directions which future research should take.

ACKNOWLEDGMENTS

In addition to the author's own thoughts on problems and suggestions for research on Sudbury, drawn from the experience of many years' work, the author has drawn extensively on the several chapters in this Special Volume and would very much like to thank the authors of these chapters for the ideas they have contributed.

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CHAPTER 25

Summary, Discussion, and Synthesis

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ABSTRACT

The Sudbury Structure straddles the erosional contact between Archean tonalitic gneisses and quartz monzonites to the north and basalts and rhyolites, wackes, and quartz arenites of the Huronian Supergroup to the south. A major east-striking structure, the Murray Fault Zone, lies just to the south of Sudbury and is the line about which sedimentation in the Huronian changes from a thin sequence of dominantly fluvial beds to the north, to a much thicker succession of shallow marine sediments to the south.

The Sudbury Structure is situated at about the mid-point of the east-trending Elliot Lake-Englehart positive gravity anomaly. A detailed analysis of the anomaly as it occurs beneath the Sudbury Structure reveals that it cannot be explained by the rocks exposed within the structure itself, but that a 60 by 40 km mass of mafic and ultramafic rock underlies the area at depths of 5 to 8 km.

The Sudbury Igneous Complex intruded the structure 1.85 Ga ago. It consists of the Lower Zone, composed predominantly of norites, the Middle Zone,

composed of gabbros, and the Upper Zone, consisting of granophyres. The Ni-Cu ores occur around the outer margin of the Complex, associated with a group of norites, gabbros, and quartz diorites known as the Sublayer.

The Footwall of the Sudbury Igneous Complex is cut by a number of breccias. A mega-breccia, composed of large blocks of gneiss is best developed close to the contact of the Sudbury Igneous Complex along the North Range. Also along the North Range, the contact itself is the locus for the Footwall Breccia; this is interpreted as the consequence of the crushing and/or melting of country rocks. The Sudbury Breccia, compared with the pseudotachylites of the Ries and Vredefort Structures, cuts all Footwall rocks older than the Sudbury Igneous Complex up to a distance of 25 km from its outer contact. Fragments in this breccia are of local derivation; the matrix has the composition of the local rocks, modified to some extent by mixing with other nearby rock types.

The Sudbury Igneous Complex is overlain by rocks of the Whitewater Group. The lowest formation of this group, the Onaping Formation, consists of 1800 m of breccias which are variably interpreted as a series of pyroclastic and ash flows, or the result of fall-back after meteorite impact. The interpretation of this formation is one of the main keys to the origin of the Sudbury Structure. Country rock fragments within the breccia display evidence of shock metamorphism, as do rocks peripheral to the structure.

The Onaping Formation grades upward into the pelagic sediments of the Onwatin Formation, which are overlain in turn by the proximal turbidites of the Chelmsford Formation. Both the Onwatin and Chelmsford Formations consist of material derived from outside the Sudbury Structure.

Points favouring an impact origin for Sudbury include the evidence of shock metamorphism and the presence of the Sudbury Breccia and the Onaping Formation, both of which have analogies at presumed impact sites. The apparent original ellipticity of the Sudbury Structure; the presence of compositional zoning, and bedding and cooling units within the Onaping Formation; the superimposition of the structure on a gravity anomaly of regional proportions; the presence of the Sudbury Igneous Complex; and the fact that work at the Vredefort structure in South Africa is indicative that shock metamorphism may also result from endogenous processes, are all points contrary to an impact origin and are supportive of an endogenous origin.

The marginal rocks of the Sudbury Igneous Complex are thought to have crystallized *in situ*. The high SiO_2 and K_2O and low CaO contents, and low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio of these rocks in comparison with those of continental flood basalts are suggestive that the magma

responsible for the Complex experienced extensive contamination by felsic country rocks. The REE profiles and major elements can be modelled if a 1:2 mixture of quartz monzonite and tonalite, that forms much of the basement at Sudbury, is combined on a 1:1 basis with a fairly primitive flood basalt ($\text{MgNo} = 0.61$). The Sublayer is more fractionated than the marginal unit of the Main Mass, but its major element and REE concentrations also suggest significant assimilation of a similar contaminant. The high Sr initial isotope ratios of both Main Mass and Sublayer are consistent with the contamination hypothesis.

The ore deposits can be grouped into (1) those that occur along the North Range, in which the sulphides occur largely within Footwall Breccia and in fractures in the underlying gneiss, (2) those that occur along the South Range, in which much of the sulphide either occurs at the contact between the Sudbury Igneous Complex and the Footwall rocks or within marginal phases of the Complex and (3) those associated with dikes of Sublayer projecting into the Footwall of the Complex, in which the sulphides mostly occur in pipes rich in inclusions that are oriented subvertically within the dikes.

Mafic and ultramafic inclusions are restricted to variants of the Sublayer that are also mineralized. These inclusions have REE profiles with high La/Yb ratios similar to those of the Main Mass and Sublayer. The Fo content of olivines in the inclusions indicates that they crystallized from liquids spanning the same range of MgNos as is spanned by samples of the Sublayer. It is proposed that the inclusions have been derived from cumulus layers that formed as the Sublayer magmas fractionated.

The contamination that gave rise to the SiO_2 -rich composition of the Complex is believed to be the cause of the segregation of large amounts of sulphide. It is suggested that the close association between sulphides, inclusions, and Sublayer magmas is the consequence of the sulphides and ultramafic and mafic cumulates settling together in hidden sills that are present peripheral to and beneath the Complex. These are responsible in part for the gravity and aeromagnetic anomalies. They were injected into the fractures in the rocks beneath the Complex as offshoots from the main magma conduit. As they cooled and fractionated, residual magma rose to the floor of the crater that now holds the Complex to form the presently exposed Sublayer. Where magma from a deeper sill cut and disrupted an overlying sill, it picked up sulphides and inclusions, and carried them upward to form the ore deposits.

The magma of the Main Mass of the Complex, cooling in part within the central conduit, did so more slowly than the Sublayer. It thus became more contaminated but less fractionated. It was injected into its

present position as a series of pulses at essentially the same time as the Sublayer, possibly in response to structural adjustments taking place in the overlying crater.

INTRODUCTION

Scientists with many different backgrounds, experiences, and perspectives have contributed to this volume. Inevitably, this has led to a variety of interpretations of the very complicated history of the Sudbury Structure. This summary is one person's attempt to assess which interpretations, at this date, seem reasonably certain, which of the often contradictory explanations that have been proposed for certain phenomena still remain as viable alternatives, and then to construct a scenario which can account for as much of the observational and interpretative data as possible.

Amongst the many questions that have arisen with respect to the geology of Sudbury as it has been unravelled over the past 100 years, 3 stand out above all of the others.

1. What catastrophe (because whatever happened it was most certainly catastrophic) produced the Sudbury Basin, the fractured and brecciated Footwall Rocks, and the 1800 m of Onaping Formation?
2. What triggered and controlled the emplacement of the Sudbury Igneous Complex and what accounts for its unusual composition?
3. Why did such a large amount of sulphide segregate from certain phases of the Complex?

In this summary, each of these questions is discussed in turn.

DEVELOPMENT OF THE SUDBURY STRUCTURE

Regional Setting

GEOLOGICAL EVIDENCE

The oldest rocks in the Sudbury area are those of the Archean Levack Gneiss Complex (Card *et al.*, Chapter 2, this volume). They include migmatitic tonalitic gneiss, with mafic layers and xenoliths, migmatitic paragneiss, tonalitic intrusions, and mafic, ultramafic, and gabbro-anorthosite intrusions; all were metamorphosed to upper amphibolite or lower granulite facies.

Zircons from several samples of the Levack Gneiss Complex indicate an original age of 2.711 ± 0.007 Ga and a major disturbance leading to some Pb-loss at about 1.836 ± 0.014 Ga (Krogh *et al.*, Chapter 20, this volume). A pegmatoidal mobilizate

within the gneiss has been dated at 2.647 ± 0.002 Ga. The gneiss has been cut and retrograded by undeformed Algoman granites whose ages are in the 2.50 to 2.65 Ga range. Card *et al.* (Chapter 20, this volume) believe that the high grade of the gneiss is the result of pronounced domical upwarping in the vicinity of Sudbury, which has exposed rocks that were metamorphosed at or near the base of the crust; this is similar in some respects to the linear upwarping that has occurred along the Kapuskasing structure (Percival and Card 1983). Since the Algoman granites are unmetamorphosed and undeformed, Card *et al.* (this volume) conclude that the upwarping at Sudbury occurred before intrusion of these rocks.

The Archean rocks are overlain by rocks of the Huronian Supergroup. These consist of local accumulations of basalt and rhyolite, and more widespread turbidites, conglomerates, siltstones, arkoses, and quartz arenites of the Elliot Lake, Hough Lake, Quirke Lake, and Cobalt Groups. Formations within these groups thicken to the south and east. The line, along which the southward thickening and consequent downwarping of the basement becomes pronounced, corresponds to that of the present Murray Fault Zone. The upper group of the Huronian Supergroup, the Cobalt Group, is more extensive than those underlying it, and extends well to the northeast of the Sudbury area.

The Elliot Lake Group includes the rhyolite Copper Cliff Formation, with a U-Pb age of $2.45 \pm 0.025/-0.010$ Ga (Krogh *et al.*, Chapter 20, this volume) and has been cut by the $2.333 \pm 0.030/-0.023$ Ga-old granitic Creighton Pluton (Frarey *et al.* 1982), and by the $2.388 \pm 0.020/-0.013$ Ga-old granitic Murray Pluton (Krogh *et al.*, Chapter 20, this volume). All of the Huronian Supergroup is cut by the Nipissing Diabase (2.11 ± 0.08 Ga, Van Schmus 1965¹).

The overall tectonic-depositional picture is one of early east-west graben faulting with associated mafic volcanism being followed by major broad scale subsidence occurring to the south of the Murray Fault Zone. Sediment carried by mainly south to southeast-flowing rivers filled the zone of subsidence. There are a number of cycles in which downfaulting in this zone was followed by debris flows and deep water deposition, which then gave way to generally prevailing fluviatile, deltaic, and shallow marine conditions.

Models that have been proposed for the pre-Sudbury Event Proterozoic development in the region include those of an east-trending graben or ensialic basin (Card and Hutchinson 1972; Card 1978; Sims *et al.* 1980) and an aulacogene opening to the east (Young

¹Rb-Sr ages presented in this summary are those of the original authors, recalculated using the new decay constant for ⁸⁷Rb of 1.42×10^{-11} . The ages are, therefore, in some instances, younger than those given in the original text.

1982). Van Schmus (1976), Cambray (1978), Larue and Sloss (1980), and Zolnai (1982) have suggested that the Huronian rocks were deposited along the southeastern margin of a continent. Subduction (northward according to Van Schmus (1976), southward according to Cambray (1978) and Larue and Sloss (1980)), followed by continent-continent collision resulted in the northward thrusting and crustal shortening of the Penokean Orogeny that affected the Southern Province 1.85 Ga ago.

Innes and Colvine (Chapter 3, this volume) point out that the Sudbury region was a Ni-Cu rich metallogenic province 600 Ma prior to the intrusion of the Sudbury Igneous Complex. Ni-Cu mineralization accompanying early Huronian mafic igneous activity was followed by that related to the Nipissing Diabase. The Nipissing Diabase is zoned with respect to its associated mineralization: in the Cobalt area, northeast of Sudbury, this consists primarily of Ag-Co-Ni-As veins; west of Sudbury, Cu-carbonate veins are the dominant mineralization; it is only in the Sudbury area that small concentrations of Ni-Cu sulphides predominate in the Nipissing Diabase.

GEOPHYSICAL EVIDENCE

Card *et al.* (Chapter 2, this volume) present regional magnetic and Bouguer gravity maps of the region (Map NL-17AM and Chart A, back pocket). Apart from anomalies which are attributable to well-known features such as the Kapuskasing lineament, the most striking feature of the gravity map is the positive anomaly extending from Elliot Lake to Englehart (Card *et al.*, Chapter 2, this volume, Figure 2.6) and passing through the Sudbury Structure. The apparent density of the body responsible for this is 2.75 to 2.85 g/cm³, which indicates that it is likely to be mafic gneiss or amphibolite. Relatively little of this is exposed in the area marked by the anomaly, although enclaves of mafic material provide limited support for the interpretation.

The magnetic map indicates 2 anomalies in the vicinity of Sudbury. The larger anomaly is located just to the west of Lake Temagami, which lies to the east of Sudbury; the smaller anomaly is that centred on the Sudbury Structure itself. Card *et al.* (Chapter 2, this volume) conclude that the remainder, after the subtraction of a short-wave component attributable to iron formation from the Temagami anomaly, can be explained by calling upon the presence of a large mass of possibly serpentized ultramafic rock, that extends from a depth of 3 to 18 km, with a width of from 5 to 15 km. There is a suggestion that part of it has a funnel-shaped cross-section. Both the Sudbury and Temagami magnetic anomalies are coincident with the Elliot Lake-Englehart gravity anomaly.

The North Channel of Lake Huron, between Manitoulin Island and the mainland, is marked (Card *et al.*, Chapter 2, this volume, Figure 2.5) by an intense magnetic low. Modelling indicates that magnetic susceptibilities are anomalously low between Manitoulin Island and the Murray Fault Zone to the north, indicating an atypical basement in this area. Card *et al.* speculate that this may represent a zone of intense shearing along which oxidizing solutions have moved, oxidizing the rocks and lowering their magnetic susceptibility. They suggest that this represents the suture and related faulting and fracturing associated with the postulated Penokean continental collision that has been discussed above.

Gupta *et al.* (Chapter 18, this volume) analyse the combined gravity and magnetic anomaly that marks the Sudbury region itself. Popelar (1972) had interpreted the +30 mgal gravity anomaly in the vicinity of Sudbury as a consequence of the rocks of the Sudbury Igneous Complex and adjacent "greenstones". However, in order to explain the magnitude of the anomaly, he had to assume that the crust had an average density of 2.65 g/cm³. Gupta *et al.* (Chapter 18, this volume) take issue with this assumption, pointing out that 3400 density measurements made between the Quebec border and Sudbury give a total weighted background density of 2.73 g/cm³ for the region. The low regional background density assumed by Popelar cannot be ascribed to particularly low density rocks in the immediate vicinity of Sudbury, since the granitic bodies (average density 2.63 g/cm³) produce distinct negative gravity anomalies. This implies that the average density of the upper crust in the region is higher than 2.65 g/cm³. Thus, for the most part, it likely consists of dense amphibolite or granulite facies gneisses and associated mafic rocks of the Levack Gneiss Complex; these have a mean measured density of 2.77 g/cm³.

After subtracting a large-scale regional or normal Bouguer gravity field from the gravity map, the anomalous Bouguer gravity field was further separated into a regional (called the "Sudbury gravity anomaly") and a residual component by Gupta *et al.* (Chapter 18, this volume). The Sudbury gravity anomaly was expressed as either due to 2 single peaked, overlapping positive anomalies, designated as a northern one and a southern one (model A); or a single positive anomaly with a smaller, -5 mgal depression superimposed on it near its centre (model B).

Gupta *et al.* (Chapter 18, this volume), therefore, explore 2 alternative explanations. The first (model A) is that the Basin is underlain by 2 masses of mafic and ultramafic rock, one underlying the North Range and the other underlying and extending well to the south of the South Range. The second (model B) is that the Basin is underlain by a single mass of mafic and ultra-

mafic rock, and that low density rocks associated with the Sudbury Structure itself give rise to the superimposed negative anomaly. Both models lead to the conclusion that a large (60 by 40 km) mass of mafic rock, with densities similar to gabbro or gabbro-anorthosite ($3.02 \pm 0.03 \text{ g/cm}^3$) underlies and extends beyond the Sudbury Igneous Complex, as is indicated in Figures 18.15 and 18.16. The main difference is that, at their deepest, the tops of the masses are at a depth of 7 to 8 km according to model A and 5 km according to model B.

Turning to the regional magnetic map, Gupta *et al.* (Chapter 18, this volume) conclude that a tabular body, roughly coincident with the mass postulated on the basis of gravity to underlie the North Range, can account for much of the magnetic profile. A smaller, more deeply buried mass (at a depth of 8 to 9 km), just to the south of the axis of the Sudbury Structure, also seems to be indicated. They suggest that partly serpentinized ultramafic rocks can account for the magnetization of the rocks underlying the Sudbury Structure. If these anomalies (attributed to buried rocks) are subtracted from the total field, then the residual anomalies are explicable on the basis of the known distribution and magnetic susceptibilities of the rocks of the Sudbury Igneous Complex, using magnetic vectors that are consistent with the determinations of Larochelle (1969) and Morris (Chapter 19, this volume).

Scribbins *et al.* (1984) (see discussion of Naldrett *et al.*, Chapter 11, this volume) have described a series of ultramafic and mafic inclusions occurring within the Sublayer of the Sudbury Igneous Complex. These range in composition from dunite, through peridotite, clino- and orthopyroxenite, to olivine gabbro, gabbro, and norite. Some of the inclusions can be identified with certainty as coming from the Nipissing Diabase. The majority, however, are not of this type, nor do they represent any rock types that are observed *in situ* as part of the Complex. Scribbins *et al.* (1984) concluded that the inclusions have been derived from some hidden layered intrusion (or intrusions), but they were unable to determine whether this (these) was (were) part of the Complex or not. The question now arises as to whether they have been derived from Gupta *et al.*'s (Chapter 18, this volume) postulated intrusion, something that Scribbins *et al.* (1984) were unaware of. Further work addressing the age of the inclusions and their ability to account for the intensity of the remnant magnetization demanded by Gupta *et al.*'s models are required before this question can be answered with certainty. Later in this section, chemical criteria are discussed which indicate some close similarities between the inclusions and the rocks of the Sudbury Igneous Complex. It is this author's current view that they are related to the Complex, and this is brought out in the model proposed at the end of this summary.

Local Setting

Some very unusual features mark the local setting of the Sudbury Igneous Complex. At least 3 distinctive, pre-Complex breccias occur in the Footwall and at least 2 overlie the Complex. Here, the Footwall rocks are discussed first, followed by those of the hanging wall.

FOOTWALL OF THE SUDBURY IGNEOUS COMPLEX

Unusual features within the Footwall rocks include (1) upturning and brecciation, (2) shock metamorphism, (3) the Sudbury Breccia, and (4) the Footwall Breccia.

Upturning and Brecciation

Although regional folding has given Huronian strata a steep, even overturned attitude along much of the North Shore of Lake Huron (Card *et al.*, Chapter 2, this volume), Dressler (Chapter 6, this volume) emphasizes that localized upturning of strata appears to be related to the Sudbury Igneous Complex. In Falconbridge and Garson Townships, he reports that over a distance of 500 m, the southerly dip of strata increases from 20° to 85° on approaching the contact. Morris (Chapter 19, this volume) concludes from paleomagnetic studies that the South Range has been rotated at least 55° towards the north about its strike direction, so that any steeply dipping strata would have dips this much steeper and any overturned strata attitudes this much more overturned prior to cooling of the Complex. It is not possible to look for similar deformation within the Levack Gneiss Complex, since the gneisses do not lend themselves to the same kind of analysis. However, Greenman (1970) has pointed out that brecciation of the Levack rocks becomes very much more pronounced over a distance of about 1 km on approaching the Sudbury Igneous Complex.

Shock Metamorphism

Shatter cones were first described at Sudbury by Dietz (1964) who attributed them to a shock wave generated by the impact of a meteorite. Subsequently Guy-Bray *et al.* (1966) and Dressler (Chapter 6, this volume) have documented many other locations (Dressler, Chapter 6, this volume, Figure 6.4). Guy-Bray *et al.* concluded that once strata were rotated back to their orientation prior to the Sudbury Event, the axes of all cones intersected at a point slightly above the centre of the basin. Dressler disputes this, pointing out that cones with opposite orientation are found within the same locality. Fleet (1979) has proposed that shatter cones developed in response to stresses generated during the Penokean Orogeny, but Pattison (1980) has shown that the cones are related to the Sudbury Structure.

Other evidence of shock metamorphism observed in the Footwall rocks (Dressler, Chapter 6, this volume) at Sudbury include kink bands in biotite (observed up to 10 km from the contact of the Complex), planar features in quartz (requiring 100 and more kb of shock pressure to form and observed up to 5.5 km into the Footwall from the Complex), and planar features in plagioclase (requiring pressures of from 150 to 300 kb to form and observed up to 2.9 km into the Footwall).

Sudbury Breccia

This breccia occurs as dikes and irregular bodies cutting all rocks older than the Sudbury Igneous Complex outside of the Sudbury Basin. Bodies range from a few cm to 11 km in length. Dressler (Chapter 6, this volume) has shown that bodies of breccia are abundant up to distances of 5 to 10 km from the Complex, and then occur sporadically beyond this to a distance of about 25 km, where they again become common. In some localities, breccia has been observed as far as 50 km from the Complex.

Peredery and Morrison (Chapter 22, this volume) have distinguished 3 types of Sudbury Breccia: (1) massive breccia with an aphanitic matrix, (2) breccia with an igneous matrix, and (3) flow-banded breccia. Type (1) is the principal type and is that discussed by Dressler (Chapter 6, this volume). Type (2) occurs as wisps and patches in type (1) and is taken to indicate that the formation of the type (1) breccias was, in places, accompanied by melting. Type (3) forms separate bodies, and Peredery and Morrison ascribe it to mylonitization along faults as the Sudbury Basin at-

tempted to reach gravitational equilibrium after its excavation.

Fragments in the Sudbury Breccia are mostly of the immediate host rock, although exotic fragments are also common. The maximum size of fragments tends to vary with the size of the body in which they occur, but in general, they range from microscopic up to a few m in diameter. Most of the larger fragments are subrounded.

The matrix consists of fine rock and mineral flour ranging from microscopic to submicroscopic in size. Dressler (Chapter 6, this volume) points out that while the composition of the matrix is related to that of the host rock (Table 25.1 and Figure 25.1), it tends to have been modified in a direction towards an average composition. For example, SiO_2 in the matrix of breccia cutting granite and arkose has been lowered with respect to that of the host rock, while that in breccia cutting diabase and gabbro has been raised. MgO and FeO in the matrix of breccia cutting granite and arkose have been raised and that in breccia cutting diabase and gabbro lowered. The gneiss has a composition intermediate between that of granite and basalt and, as might be expected, the major element compositions of breccia matrix and gneiss are very similar.

Dressler describes vesicles in some of the breccia matrix. He also describes shock lamellae in quartz; plastically deformed angular, shard-like fragments of rock with flow lines, representing possible recrystallized glass; and possible diaplectic and spherulitic plagioclase. He concludes that the Sudbury Breccia strongly resembles bodies of pseudotachylite that were

TABLE 25.1: AVERAGE COMPOSITION OF SUDBURY BRECCIA MATRIX AND HOST ROCK.

	1 Granite	2 Bx	3 Gneiss	4 Bx	5 Diabase	6 Bx	7 Gabbro	8 Bx	9 Arkose	10 Bx
SiO_2	70.4 (2.82)	63.4 (6.03)	64.8 (5.39)	63.4 (4.8)	51.2 (2.8)	55.8 (3.1)	50.5 (0.20)	67.2 (5.9)	83.0 (5.2)	73.6 (1.99)
Al_2O_3	15.6 (1.76)	14.8 (1.4)	16.2 (0.67)	16.3 (0.73)	13.3 (0.80)	14.4 (1.4)	8.89 (1.85)	10.7 (0.77)	8.51 (1.57)	12.7 (1.2)
FeO^*	2.20 (0.83)	6.21 (2.39)	4.35 (1.39)	5.42 (1.86)	13.5 (0.68)	9.93 (2.17)	9.94 (0.98)	5.54 (1.61)	0.98 (0.92)	3.40 (1.19)
MgO	0.73 (0.49)	2.62 (1.41)	2.43 (1.42)	2.36 (1.59)	4.92 (1.86)	3.51 (0.59)	14.8 (1.67)	6.53 (2.30)	0.33 (0.54)	1.32 (0.50)
CaO	1.96 (1.02)	3.70 (2.03)	3.48 (0.88)	4.43 (0.83)	7.36 (1.31)	4.86 (1.00)	9.65 (0.88)	3.82 (2.02)	1.32 (1.07)	0.55 (0.25)
Na_2O	3.93 (1.12)	3.95 (1.15)	3.89 (0.24)	4.10 (0.33)	3.17 (0.89)	3.55 (0.50)	0.65 (0.26)	2.09 (0.66)	2.86 (1.09)	2.25 (0.96)
K_2O	3.33 (1.81)	2.75 (1.70)	1.80 (0.55)	1.11 (0.14)	1.06 (0.38)	2.92 (1.80)	0.53 (0.29)	0.64 (0.47)	1.16 (0.67)	2.90 (0.70)
TiO_2	0.46 (0.18)	0.89 (0.45)	0.78 (0.17)	0.92 (0.12)	1.84 (0.42)	1.40 (0.57)	0.58 (0.08)	0.60 (0.13)	0.38 (0.16)	0.56 (0.12)
Number of Samples	12	12	3	4	4	4	8	9	3	3

Note

Figures in parentheses are standard deviations.

FeO^* = Total Fe calculated as FeO

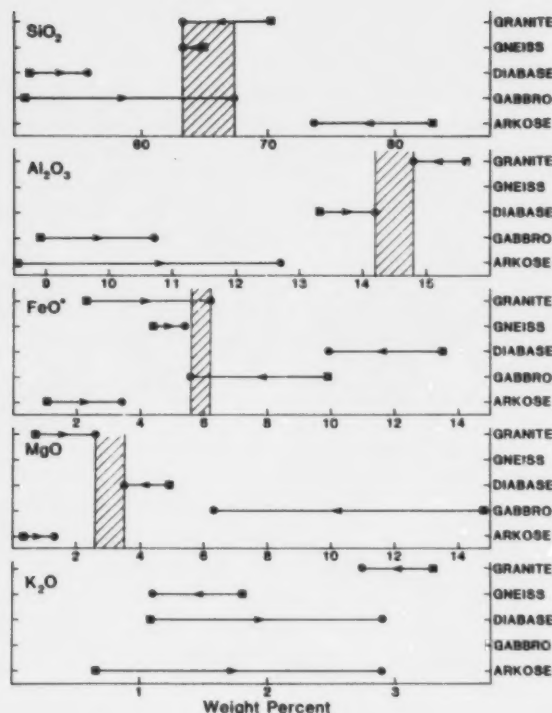


Figure 25.1. Concentrations of some major elements in the matrix of the Sudbury Breccia compared with their concentrations in country rocks to the breccia. Concentrations in the country rocks are shown by squares and in the related breccia matrix by circles. Note that in almost all cases, the breccia matrix has an intermediate composition, less extreme than the country rocks. Data from Dressler (this volume). All concentrations are in wt%.

first defined at the Vredefort structure, South Africa (Shand 1916; Wilshire 1971). Similar bodies have also been described from the Ries crater in South Germany (Dressler and Graup 1969; Stoffler *et al.* 1977) and the Manicouagan impact structure in Quebec (Dressler 1970; Murtaugh 1976).

Sudbury Breccia has never been observed to cut rocks inside the outer perimeter of the Sudbury Igneous Complex, and it is reasonably certain that its formation pre-dated intrusion of the Complex. Speers (1957) attributed formation of the breccia to volcanic processes that were accompanied by periodic uplift and then collapse of an igneous dome centred on Sudbury. However, since the proposal of the impact hypothesis, many authors (including Dietz (1964) and French (1968)) have ascribed its formation to impact, pointing to its similarities with the pseudotachylite found at believed impact sites. Dressler (Chapter 6, this volume) concurs with this explanation suggesting that the breccia originated mainly by brittle fracture and the comminution of Footwall rocks during the explosive event. Explosion was immediately followed by implosion, as masses of rock burst apart, creating

voids within themselves into which fragments and breccia matrix were sucked.

The actual origin of the breccia is clearly closely related to whatever catastrophe created the Sudbury Structure. With its evidence of cataclasis, vesicles, glass, igneous-textured matrix in some areas, and shocked minerals, the breccia bears witness to the catastrophic nature of the event, but, within itself, does not appear to contain the answer to the cause.

Footwall Breccia

This breccia forms discontinuous lenses and sheets along the Footwall of the North and East Ranges of the Sudbury Igneous Complex. Along the South Range, certain masses of breccia have been equated with it (*see* Dressler, Chapter 6, this volume) but such occurrences are not common.

Contacts with the overlying Sudbury Igneous Complex may be sharp, with either rocks of the Complex intruding the breccia, or dikes of breccia cutting back into the Complex; they may also be gradational, where the Sublayer of the Complex has incorporated much Footwall Breccia. Contacts with the Levack Gneiss Complex are commonly sharp, with breccia matrix occurring as veins, which narrow down to fine stringers, penetrating the Footwall and surrounding, or partly surrounding blocks of gneiss.

Fragments within the breccia are mostly identifiable as originating from the Footwall, except close to the contact of the Complex. Greenman (1970) documented fragments in the Footwall Breccia at the Strathcona Mine that belong to the suite of inclusions found in the Sublayer. Burkhard O. Dressler (Geologist, Ontario Geological Survey, personal communication, 1984) has pointed out that this is not common and that he has not observed similar inclusions in the Footwall Breccia elsewhere. Fragments identifiable as belonging to the igneous matrix of the Sublayer itself have not been identified. Nowhere do the fragments show pronounced alignment; this, coupled with their local derivation, suggests brecciation in place without flow.

The matrix of the breccia consists primarily of small stubby plagioclase laths, rounded quartz grains, and wispy remnants of pyroxene and amphibole, cemented by flood quartz. Granophyric texture is present in some localities, indicating that partial melting has occurred. The proportion of granophyre may increase so that it becomes the dominant constituent of the rock. Dressler (Chapter 6, this volume) describes kink banded mica and planar features in quartz of mineral and rock fragments from the breccia matrix. He points out that in some areas a gradation occurs from Footwall Breccia to Sudbury Breccia away from the Complex. He regards the 2 breccias as being produced

in a very similar manner, and attributes the change in grain size and colour accompanying the gradation to metamorphism by heat from the Complex.

Dressler regards the Footwall Breccia mainly as a parautochthonous mass of crushed rock that remained lining the crater walls after meteorite impact. This is consistent with the pre-Sudbury Igneous Complex age relationships observed in some areas. Dressler points out, however, that a lining of this kind has not been described in detail from other believed impact sites, although one drillhole into the Ries crater revealed 100 m of brecciated material that has some similarities with the Footwall Breccia at Sudbury. Coats and Snajdr (Chapter 14, this volume) draw attention to the pyroxene hornfels aureole that surrounds the Sudbury Igneous Complex and extends up to 1 km into the Footwall. These authors suggest that injections of the Complex disrupted and melted Footwall rocks along the North Range giving rise to a breccia of the more refractory constituents of the gneisses in a matrix of partly melted Footwall. A similar explanation was not proposed by Greenman (1970), because he observed very few rocks with textures indicative of melting in his study of the Footwall Breccia at the Strathcona Mine.

Neither Dressler's nor Coats and Snajdr's explanations are consistent with the presence of the suite of mafic and ultramafic xenoliths which are found in the breccia, and which are believed to have been introduced in Sublayer magmas, nor are they consistent with the fragments of Ni-Cu sulphide ore that were described by Pattison (1979) as present in the Footwall Breccia. Both of these observations indicate that at least parts of the Footwall Breccia post-date some units of the Complex. Greenman (1970) and Naldrett *et al.* (1972) addressed these problems and proposed that phreatic explosions had occurred within the water-saturated breccia as it became heated after intrusion of the Complex, and that this had resulted in the incorporation of material from the Complex into the breccia.

ROCKS OVERLYING THE COMPLEX

The rocks overlying the Sudbury Igneous Complex belong to the Whitewater Group, which consists of 3 formations, the Onaping, Onwatin, and Chelmsford Formations. Of these, the Onaping Formation is the most controversial, and its interpretation is one of the most important keys to understanding the Sudbury Structure.

Onaping Formation

The Onaping Formation is described in detail by Muir and Peredery (Chapter 7, this volume) who subdivide it into 3 members, the Basal Member, the Gray Member, and the Black Member, plus a series of irregularly distributed Melt Bodies.

The Basal Member forms a discontinuous zone up to 300 m thick at the base of the Onaping Formation, between the Gray Member and the underlying granophyres of the Sudbury Igneous Complex. It is intruded by granophyres, which contain inclusions and rafts of the Basal Member itself and of the Gray Member. The Basal Member consists of a number of different breccia types, some fragment-supported, others matrix-supported. The breccias form discrete bodies which are erratically distributed in terms of their size, shape, and nature of the fragments that they contain.

The fragments consist of a variety of country rock types. On the North Range, these are largely 'granitic', together with lesser proportions of meta-sandstones and some tonalitic gneisses. On the South Range, they consist predominantly of sedimentary rocks, with quartz arenite being particularly common. Many of the fragments in the Basal Member show evidence of having been subjected to shock metamorphism (*see below*).

The matrix is generally very fine grained, and is composed largely of felsic minerals (35 to 60% plagioclase; 25 to 45% quartz; 10 to 40% potassic-feldspar) intergrown with an igneous to sub-igneous texture, and with a speckling of mafic minerals, which have given rise to the field term 'pepper and salt' rock.

The Melt Bodies consist of lens-like, oval, and irregular masses concentrated in clusters or groups at the base or in the lower part of the Gray Member. They contain numerous fragments of rock types similar to those found in the underlying Basal Member. The fragments account for up to 80% of the Melt Bodies by volume, and range from 1 cm to more than 1 m in diameter. They are set in a matrix which may be quartz-rich (27 to 51% quartz), plagioclase-rich (61 to 75% plagioclase; 3 to 23% quartz), or granophyric (8 to 44% granophyre). Plagioclase grains have an elongate habit which is interpreted as indicating that the Melt Bodies were indeed 'melts'. In some areas, the bodies have sharp contacts with the Basal Member, but in others it is gradational. Their contact with the Gray Member is always sharp.

The Gray Member is continuous around the Sudbury Structure, varying from 200 to 700 m in thickness. It consists of a variety of breccias, differentiated largely on the basis of fragment size and abundance, occurring as a series of lenses of limited continuity, stacked together irregularly.

The breccias range from monolithic to heterolithic, and from matrix-supported to fragment-supported. Fragments comprise crystalline basement rocks, metasedimentary rocks, and a variety of other types including material interpreted as recrystallized glass. The basement material accounts for 20 to 40%

of the fragment population, and consists predominantly of 'granite'; gneissic fragments are surprisingly uncommon in view of the great abundance of gneiss in the basement. The metasedimentary fragments account for 60 to 80% of the population, and are mostly quartz-rich types, primarily quartz arenites and arkoses; it is again surprising that wackes and volcanic rocks from the basement are distinctly underrepresented. Fragments range from many m to < 1 cm in diameter, but the majority have diameters ranging from 1 to 64 cm. About 10% of the country rock fragments exhibit relicts of shock features. Many fragments are enclosed or partly encircled by a flow-banded material that is interpreted as recrystallized glass. The matrix consists of comminuted fragments of original glass and a variety of small fragments.

Muir (Chapters 7 and 21, this volume) emphasizes that his work on the Onaping Formation near the East Range has shown that units with sharp contacts, cooling units, and units deposited on terrain with primary erosional relief are not uncommon. He states that these features are also much more abundant elsewhere in the Gray Member than has been implied in the recent literature.

The Black Member is also continuous around the Sudbury Structure, varying from 800 to 1200 m in thickness. It is less variable than the Gray Member. Individual zones of breccia can be distinguished on the basis of their variable abundance of MgO-rich shards and the size of their fragments, but these variations occur over distances of a few cm to a few m.

Contacts with the underlying Gray Member vary from gradational to sharp. Where they are sharp, they are often marked by an abundance of chlorite-rich shards, presumably derived from an MgO-rich parent.

Laminar bedding (as contrasted to units of breccia which define bedding on the basis of fragment size) is largely confined to the upper 1/3 of the member; near the East Range, 2/3 of the way up-section, Muir (1983) has traced a 10 cm thick unit for 35 m, striking at an angle of 135° in contrast to the regional strike of 065°.

Fragment types are the same as in the Gray Member, although their average diameter is very much less. One distinguishing feature between the 2 members is the abundance of sulphide fragments which, although found in both, are very much more common in the Black Member, accounting on average for somewhat < 1% of the total volume of this member. The sulphide fragments consist of varying proportions of pyrrhotite, chalcopyrite, pyrite, and sphalerite in decreasing order of abundance.

The difference in colour between the 2 members is due to the presence of elemental carbon in the Black Member; the carbon content ranges from 0.2 to 0.75 and averages about 0.4 wt %.

Chemical Composition of the Onaping Formation: Muir and Peredery (Chapter 7, this volume) present analyses for a series of samples selected from the different members of the Onaping Formation to exclude as much of the included fragmentary material as possible. There is an overall progression in the data for the 4 main divisions from felsic to mafic upward in the stratigraphic succession. The matrix of the Basal Member ranges in composition from dacite to andesite; matrix in the Melt Bodies ranges from andesite to basalt (as do the fragments of flow-banded glasses, which have very similar compositions to the melt body matrix); the matrix of the Gray Member has the composition of calc-alkaline basalt, and that of the Black Member, which shows only a restricted range in composition, resembles tholeiitic basalt. All of the units except the Black Member have a pronounced calc-alkaline affinity. The matrix of the Melt Bodies has an overall composition similar to that of the Plagioclase-rich Granophyre of the Sudbury Igneous Complex, which it also resembles in the composition of its plagioclase and pyroxene.

Peredery (1972) reported that recrystallized, devitrified, glassy material forming shards in the matrix, and flow banded material occurring as rims to country rock inclusions and as discrete bodies in the Onaping Formation, have very heterogeneous compositions with Al_2O_3 ranging from 3 to 20, SiO_2 from 53 to 70, MgO from 1.2 to 12.7, and Na_2O from 0.5 to 12 wt %.

Shock Features in the Onaping Formation: Shock features are found in fragments of all units of the Onaping Formation. They include: (a) oriented planar features within quartz and feldspar (indicative of pressures of 50 to 150 kb; 200°C); (b) evidence that maskelynite formerly pseudomorphed feldspar, and of the former glassy state of other minerals (indicative of 150 to 380 kb; 450°C); (c) partial melting of titanite and zircon (indicative of 380 to 500 kb; 1600°C); and (d) evidence that grains of quartz and feldspar melted and became plastically deformed, but that no mingling occurred between adjacent minerals to form a minimum melting mixture of intermediate composition; this argues for transient melting such as occurs during the adiabatic compression associated with the passage of a shock wave.

Onwatin Formation

The Onwatin Formation is described by Rousell (Chapter 8, this volume). It consists of a sequence of carbonaceous, pyritic, and massive argillites and siltstones, together with minor amounts of greywacke mainly near the top contact. Estimates of the thickness range from 600 to 1400 m, although Rousell (Chapter 5, this volume) believes that structural deformation has led to exaggerated estimates of thickness and that the lesser figure is the more likely.

The total carbonaceous content in the Onwatin Formation varies from 0.63 and 7.72% C and the free C content from 0.26 to 4.05%. Under the microscope, the free C can be seen to be present as elongated, segmented structures that resemble modern and fossil algae and fungal filaments.

The lower contact with the Black Member of the Onaping Formation is gradational. On passing upward across the contact, there is a gradual decrease in the grain size and in the proportion of rock fragments, and an increase in the proportion of quartz. The Vermilion Member of the Onwatin Formation is developed discontinuously at the base of the formation. The Vermilion Member averages 43 m in thickness and consists of the following rock types from bottom to top; argillite, carbonate, cherty carbonate, chert breccia, interbedded argillite, limestone, and dolostone.

Rousell (Chapter 8, this volume) concludes that the bulk of the Onwatin Formation consists of pelagic sediments that have been derived from a source external to the Sudbury Basin. He states that the conclusions of Sadler (1958), based on trace element data, that the Onwatin Formation was derived from the Onaping Formation, have not been born out by subsequent work on the Onaping Formation, which has shown it to be chemically very heterogeneous.

The Vermilion Member contains sulphides which have been mined at the Vermilion and Errington deposits. The average grade of the 2 deposits is quoted by Rousell as 0.94% Cu, 4.07% Zn, 1.30% Pb, 53.5 gm/t Ag, and 0.65 gm/t Au. The sulphides occur disseminated in carbonate and as massive zones at the base of carbonate horizons and replacing the underlying argillite. The stratiform nature of the deposits makes it likely that they are the result of subaqueous exhalations. The presence beneath the waterlain Onwatin Formation of the porous, sulphide-bearing Onaping Formation, underlain itself by the hot Sudbury Igneous Complex, would have provided the ideal environment in which convection systems could have become established and then given rise to exhalative deposits on the sea floor.

Chelmsford Formation

Rousell (Chapter 8, this volume) describes the Chelmsford Formation as a sequence of proximal turbidites, approximately 400 m thick. The basal contact with the Onwatin Formation is defined as the first turbidite layer that marks the transition from the argillites, silts, and minor greywackes of the Onwatin Formation to the predominant greywacke and minor argillite of the Chelmsford Formation.

Individual turbidite cycles range from 0.4 to 5.2 m and average 1.23 m in thickness, with the most common thickness being in the range 0.2 to 0.4 m. Sedi-

mentary structures present include Fe and carbonate-rich concretions, fragments of argillite and siltstone possibly derived from the Onwatin Formation, channel structures, current marks, ripples, convolute laminations, load structures, and possible biogenic structures.

Paleocurrent directions are southwesterly, parallel to the axis of the Basin. There is no evidence of radial current flow towards the centre of the Basin. Rousell emphasizes that the lack of lithic fragments and of evidence of shock amongst the detrital grains indicate a source for the sediments that is not within the basin. Rousell believes that the most likely source is tonalite. The abrupt change from the Onwatin Formation argillites to the Chelmsford Formation turbidites suggests that the source developed rapidly during the time of the transition between the 2 formations.

Original Shape of the Sudbury Basin

Morrison (Chapter 23, this volume) suggests that if the Sudbury Structure is assumed to have had an original circular shape in plan, a number of trough-like bodies with a radial orientation, similar to those observed in lunar craters, can be postulated. He proposes that these were filled with a mega-breccia, with the intensity of the brecciation increasing toward the contact with the Complex, and that radial offsets are associated with most of them. Within the troughs, flattenings in dip, referred to at Sudbury as 'embayments', resemble the slump terraces of lunar craters. At Sudbury, the troughs are the major structures that control the Ni-Cu ores, with the embayments acting as specific loci. Morrison postulates further that "only those terraces that occur with trough embayments are known to contain ore". The existence of all of the troughs proposed by Morrison has yet to be documented, but some clearly exist, and the possibility that features of an original crater floor are fundamental to the control of the distribution of the orebodies is an important premise.

Evidence bearing on the original circular shape of the Sudbury Structure, the inward dip of its walls, and the extent to which uplift of the South Range relative to the North Range may have given rise to its present elliptical shape, is clearly important and is discussed here.

The present surface outline of the Sudbury Structure, as defined by the outer margin of the Sudbury Igneous Complex, includes a gently curving North Range, convex to the north; a tightly curving "West Range" offset by several faults; a relatively straight South Range with a north-facing convex curvature near its eastern end; and very tight curvatures at the northeastern and southeastern corners; and an East Range with an inwardly convex curvature. Dips are

variable, but average about 42°S along the North Range, 65°N along the South Range, and are steep along the East Range (Souch, Podolsky *et al.* 1969).

STRUCTURAL EVIDENCE

Rousell (Chapter 5, this volume) notes that foliation is pronounced within the Complex and adjacent Onaping and Onwatin Formations along the South Range, but becomes less pronounced north of the long axis of the basin. The foliation dips 30° to 85°S and strikes northeasterly, parallel to the axis of the basin, except at the tightly curved northeastern and southeastern corners where it is parallel to the axes of the curvatures. A lineation, defined by fragments within the Onaping Formation, occurs within the foliation plane and pitches southeasterly. There has been considerable shortening perpendicular to the foliation plane, some shortening within it perpendicular to the lineation, and extreme elongation parallel to the lineation.

Axial planes of folds identified at the base of the Onaping Formation along the South Range dip steeply southeast, with the folds overturned to the northwest. Within the Chelmsford Formation, fold axes exhibit an arcuate pattern, convex to the northwest, with the bearing of the axes varying from N48°E in the southwest to N72°E in the northeast. Axial planes of these folds are vertical and wavelengths vary from 150 to 1500 m. The folds are mostly doubly plunging, concentric in style, and comprise narrow anticlines and broad synclines.

Three groups of faults can be recognized, oriented parallel, perpendicular, and diagonal to the long axis of the structure. The parallel faults are well defined at the western end of the basin, where they dip steeply south. Displacement is thought to have been largely dip-slip with the south side up. In the case of the Cameron Creek Fault at the western end, the throw is of the order of 2000 to 3000 m. The faults are not well defined in the centre of the basin and it is likely that much of the displacement has occurred as flow.

Rousell concludes that the Sudbury Structure is a remnant of something much larger (80 km in diameter according to Dence (1972); 190 km according to Percudery and Morrison (Chapter 22, this volume)). Deformation occurred during the Penokean Orogeny in response to a 'push' from the southeast in a regime in which the maximum stress direction was horizontal and oriented northwest. The Onaping Formation behaved in a ductile manner along the South Range, becoming thickened as a result of folding and flow. The Sudbury Igneous Complex behaved as a stable plate. Rousell suggests that the inward embayment at the eastern end of the structure is the consequence of an impact event (Dence and Popelar 1972) 37 Ma ago

(Winzer *et al.* 1976), although Muir (Chapter 21, this volume) argues that there is no field evidence to support this view.

Unravelling folding in the Chelmsford Formation contributes an additional 1.6 km to the short axis of the basin. Rousell (Chapter 5, this volume) argues that there are difficulties in calculating the finite strain experienced by the Onaping Formation from measuring the present dimensions of the fragments within it and dismisses the conclusions of Brocoum and Dalziel (1974) based on these criteria. Rousell concludes that the basin was originally less elliptical than its present shape (long axis:short axis = 2:1), but that it is unlikely that it was ever circular.

PALEOMAGNETIC EVIDENCE

Morris (Chapter 19, this volume) has investigated the relative movement of the different ranges of the Sudbury Igneous Complex using paleomagnetism. Morris has found 2 remanence magnetization types that show broad-scale, systematic angular differences between the different ranges, which he terms Type 1 and Type 2. Type 1 is restricted to the norite, while Type 2 is found in both norite and granophyre. Rotation about the strikes of each of the ranges brings both of these remanence directions into good correspondence, indicating that the rotation required to achieve this reflects the actual rotation that has affected the rocks after they had cooled through their Curie points.

The required rotations (taken from Morris, Chapter 19, this volume) are summarized in Table 25.2. Stage 1 (Morris' Type 1 remanence direction) affected the norite alone and may represent subsidence at the centre of the Sudbury Structure, during cooling of the norite but before emplacement of much of the granophyre (see Naldrett and Hewins (Chapter 10, this volume) for petrologic evidence pointing to an event like this). Stage 2 post-dates cooling of the granophyre and probably records structural deformation that has affected the Sudbury Igneous Complex. If one subtracts these rotations from the present attitudes, one obtains the figures given in Table 25.2 and the picture of the original basin as a structure with shallow dips, inclined gently to the west.

Apart from the relative movement between the ranges as unified entities, Morris (Chapter 19, this volume) has tested the deformation within individual ranges, and at specific localities. He points out that the precision of paleomagnetic remanence directions derived from a number of sites along the North Range is not improved if it is assumed that the present gentle curvature is the result of the flattening of a body with an original tighter curvature, and concludes, therefore, that the present curvature of this range is original. Given this, a circular structure with this curvature

TABLE 25.2: ROTATION THAT HAS AFFECTED THE SUDBURY IGNEOUS COMPLEX, BASED ON PALEOMAGNETIC EVIDENCE.

	South Range	East Range	North Range	West Range
Rotation				
Stage 1 (Type 1)	23° N	35° W	12° S	42° E
Stage 2 (Type 2)	32° N	26° W	0-12° S	0°
Original Dips	10° N	~ 20° W	24° S	~ 0°

The rotation is about the strike direction of each respective range and is a measure of the extent to which the dip of the range has been increased in the direction indicated. Original dips are present average dips minus the rotation.

would have a diameter of at least 150 km. Morris argues that this could only be reduced to the present diameter, assuming that the total circumference of the Sudbury Igneous Complex has not changed, by major buckling of the Complex, which is not observed. However, he does not consider the possibility of vertical scissor-type faulting bringing to surface along the South Range a deeper horizontal slice through a funnel structure, particularly at the western end, with a much smaller circumference and curvature than a shallower slice.

Looking at the sharp bend at the northeastern corner of the Complex, Morris points out that once tilt corrections for the North and East Ranges have been made, there is good agreement between the remanence vectors derived from the 2 ranges. Increasing the angle between them, on the assumption that subsequent deformation has reduced this to produce the tight bend, decreases the agreement between the vectors. A statistically significant reduction in the agreement occurs if the angle between them is increased by more than 40°. Thus, the original curvature at this corner was sharp, with the present tight curvature being preferred.

Comparison of the remanence directions in the northern and southern parts of the East Range suggests that the 2 segments have been rotated by 20° with respect to one another, subsequent to cooling of the Sudbury Igneous Complex. The sense of the rotation is such that if it is counteracted, the inward embayment of the East Range is eliminated to give the range a uniform strike along its length.

Morris concludes on the basis of his paleomagnetic evidence that the preferred original form of the Sudbury Igneous Complex in plan view was that of an ellipse with sharp northeastern and southeastern corners, and that the data are against foreshortening on the scale required to generate the present shape from a circle.

CONCLUSION

A reconstruction of a possible north northwest-south southeast profile through the original structure at Sud-

bury is illustrated in Figure 25.2. In constructing this, it has been assumed that the structure was a crater, and that the Sudbury Igneous Complex was intruded along its floor. Figure 25.2A illustrates the profile of the central part at an early stage (position i), and the subsidence that is required to explain the rotation of stage 1 (position ii). Turning to Figure 25.2B, position iii is an attempt to account for the later rotation that Morris (Chapter 19, this volume) has documented as affecting mainly the South Range, coupled with the 1.6 km shortening in horizontal dimension that Rousell (Chapter 5, this volume) calls upon to explain the crumpling in the Chelmsford Formation. Position iv represents the present positions of the accessible parts of the North and South Ranges after uplift along the east-northeast faults. The reconstruction shows that if the Complex fills a crater of the type illustrated, and if the paleomagnetic and structural deductions are correct, a shortening in the north-northwest axis of the order of 12 km, from an original 42 to the present 30 km is quite likely. The present east-northeast axis is 60 km; assuming that additional, so far undocumented, shortening due to plastic strain in the rocks has not been significant, it is unlikely that the original structure could ever have been circular at the level of the present North Range.

Thus, both structural and paleomagnetic evidence indicate that the Sudbury Basin had an original elliptical shape in plan. Initial dips were gentle, but subsidence at the centre of the structure during crystallization led to a steepening of dips all around the basin. The tight curvature at the northeastern corner is original. Deformation probably associated with the Penokean Orogeny (2.0 to 1.8 Ga) resulted in the development of a foliation in the igneous rocks of the South Range and nearby rocks of the Onaping Formation, folding and thickening of the Onaping Formation, and crumpling of the Chelmsford Formation at the centre of the basin. Crustal shortening documented in the Chelmsford Formation is of the order of 1.6 km. Steepening of the dip of the South Range relative to the North probably occurred at this time. Souch, Podolsky *et al.* (1969) have argued that the South Range has been uplifted several km with respect

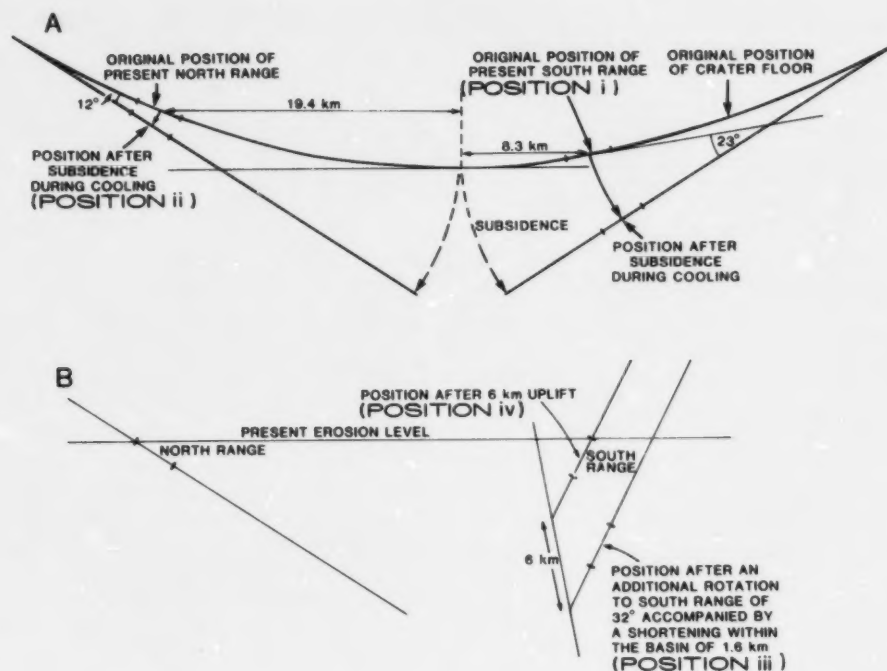


Figure 25.2. Reconstruction of a possible north northwest-south southeast cross-section through the crater at Sudbury. In (A) the original position of the floor (position i) and its rotation as a result of the subsidence that occurred during cooling of the Complex (position ii) is shown. In (B), the effect of subsequent rotation (position iii) and then upfaulting of the South Range (position iv) is illustrated.

to the North Range along steep reverse faults that are well defined at the southwestern end of the basin. The timing of this uplift is uncertain, although it is possible that it occurred during the Penokean Orogeny and subsequent orogenies. The present concave outward shape of the East Range, which originally may have been straight or slightly convex outward, may have been affected 37 Ma ago as a consequence of a meteorite impact 10 km to the east of the basin, in the vicinity of present Lake Wanapitei. It is, however, unlikely that this event could have reversed any marked original outward convexity.

The Origin of the Sudbury Structure

Both Peredery and Morrison (Chapter 22, this volume) and Muir (Chapter 21, this volume) have discussed observations on the geology of the Sudbury Basin and have reached very different conclusions as to its origin. This section is an attempt to review their data and arguments in favour of an impact versus an endogenous origin. In doing this, the author has not attempted to consider each point in turn. The author merely summarizes what he regards as the most telling points. If an item of fact or argument is omitted, it means that in his personal view it is not of critical importance.

POINTS FAVOURING AN IMPACT ORIGIN

1. Arguments in favour of an impact origin are buttressed primarily by evidence that a shock wave, several 100s of kb in magnitude, has affected the country rocks of the Sudbury area, both those presently peripheral to the Sudbury Structure and those included as fragments in the Onaping Formation.
2. The Sudbury Breccia is a widespread phenomenon that, despite Dupuis *et al.*'s (1982) assertion to the contrary, appears to be related both in space and time to the Sudbury Structure. Dressler (Chapter 6, this volume) emphasizes the marked similarities between the Sudbury Breccia and pseudotachylite veinlets described from the Vredefort, Ries, and Manicouagan structures. The latter 2 structures are widely accepted as the consequence of impact.
3. The Gray Member of the Onaping Formation, with its preponderance of fragments of country rock and glass (as opposed to identifiable volcanic fragments), general lack of stratification, and heterogeneous compositions of altered glass shards and flow-banded aphanitic-textured inclusions, is an unusual rock that has many similarities with the suevite breccia of the Ries crater in the Federal Republic of Germany. Muir (Chapter 21, this volume)

points to the distinction between 'ejecta' and 'crater' suevite. He notes that the Gray Member resembles ejecta suevite, but differs in several respects from the crater variant that is found within the Ries crater itself. The Onaping Formation is, however, preserved within the original Sudbury crater. This author comments that the mechanism of accumulation of fallback breccia is still poorly understood, and it is premature to discount the significance of the Onaping Formation on the basis of the observations at Ries. However, it is clear that this point must be addressed in the future.

POINTS CONTRARY TO AN IMPACT ORIGIN AND FAVOURING AN ENDOGENIC ORIGIN

1. Impact craters have a circular or equant polygonal shape. The Sudbury Structure is far from equant, with a long axis of 60 km and a short axis of < 30 km. Peredery and Morrison (Chapter 22, this volume) argue that the present shape is the result of deformation (a) during the waning stages of the Penokean Orogeny, (b) during intrusion of the Complex, (c) during the Grenville Orogeny and (d) as a result of the 37 Ma old impact event centred on Lake Wanapitei.

Deformation as a result of the Lake Wanapitei Event would not have increased ellipticity; rather, if it had any effect at all, it would have reduced it.

Rousell (Chapter 5, this volume) has concluded that folding in the Whitewater Series can account for a 1.6 km crustal shortening in a north-northwesterly direction. In this summary it is concluded from all of the paleomagnetic and structural information, including the faulting that has uplifted the South Range with respect to the North, that the original width of the Structure in a north-northwesterly direction might have been 42 km instead of the present 30 km. The original dimension at the same erosion level in a direction at 90° to this was in excess of the present 60 km. As is clear from Figure 25.2, any reconstruction of this kind is very dependent on the assumptions made about the original dips of the parts of the crater represented by the North and South Ranges at their current levels of erosion (Figure 25.2 is based on dips obtained by subtracting the increases in dip indicated by the paleomagnetic data from the published average dips of each range). However, it is the opinion of this author that the weight of the current evidence is against the Structure having had an original circular shape at the erosion level represented by the North Range. It is possible that this conclusion could change at some future date if more structural data are forthcoming, perhaps based upon the strain visible in the rocks of the South Range.

Muir (Chapter 21, this volume) has shown that the present outline of the Sudbury Structure is very similar to that of several volcanic calderas. He points out that the shape of the Sudbury Structure can be related to a series of fractures that are partly occupied by dikes, some of them contemporaneous with the Sudbury Igneous Complex.

2. The Onaping Formation has an overall compositional zoning of its matrix ranging from dacitic-andesitic in the Basal Member to tholeiitic basaltic in the Black Member. As pointed out by Muir (Chapter 21, this volume), this is easier to explain in terms of eruption from a zoned magma chamber than as a result of the accumulation of fallback breccia.
3. Muir (this volume) has defined cooling units and bedding in the Gray Member of the Onaping Formation (the member which Peredery and Morrison, Chapter 22, this volume, regard as fall-back breccia *per se*), and evidence of relief existing during deposition, all of which Muir claims are inconsistent with a single depositional event such as the accumulation of fall-back breccia. Several earlier workers have described the Gray Member as remarkably unstratified, but the fact that careful work has revealed stratification is significant. Impact fallback breccias are relatively unstudied and are not well understood, and it is possible that cooling units can develop. However, Muir's observations pose a question that those favouring an impact origin must answer.
4. Much of the strength of the case for an impact origin for the Sudbury Structure rests on the high pressures of 50 to 500 kb that are required to produce shock features in minerals and to induce diaplectic isotropization and melting. It is commonly supposed that the tensional strength of terrestrial rocks limits the pressure that they can sustain in anything but a transient high pressure regime, and that the pressures developed during endogenous terrestrial explosions are of the order of 5 kb (Gorshkov 1959; Walker 1980).

The Vredefort Structure in the Witwatersrand basin of South Africa is most significant in that it has associated with it all of the shock features seen at Sudbury, plus pseudotachylites similar to the Sudbury Breccia, and in addition the high pressure polymorphs of quartz (not preserved at Sudbury), stishovite, and coesite. Recent petrographic observation (referenced by Muir, Chapter 21, this volume) has been interpreted to indicate that 2 shock events, separated by a period of metamorphism and recrystallization, have affected the upturned collar rocks at Vredefort, and that shatter cones that are associated with the second event cut across breccias associated with the first. The impact of 2 meteorites in exactly the same place on 2 separate occasions is

regarded as a highly improbable coincidence. Fluid inclusions within recrystallized quartz at Vredefort are rich in CO₂, and it has been suggested that the structure is not due to impact but to a series of endogenous terrestrial explosions, possibly related to CO₂ release from mantle material.

The non-impact origin of the Vredefort structure now seems a very viable hypothesis and this casts a considerable pall on impact arguments for Sudbury, since naturally induced shock-metamorphic features no longer seem to have an exclusively extra-terrestrial origin. Precisely how shock waves of great magnitude can be produced endogenously, however, remains obscure.

5. The location of Sudbury with respect to major geophysically anomalous zones, chief among which is the Elliot Lake-Englehart anomaly, which implies unusual crustal structure.
6. The large amount of mantle-derived igneous rock present at Sudbury, which is a phenomenon unknown at other terrestrial impact sites and only rarely documented on the Moon.

POINTS THAT REMAIN CONTROVERSIAL

1. Several authors, summarized in Peredery and Morrison (Chapter 22, this volume) have remarked on the spatial relationship of the Sudbury Basin to the "triple junction" between the Superior, Southern, and Grenville Provinces, and to the near intersection of the Onaping Fault System with the Ottawa-Bonnechère graben. Peredery and Morrison (Chapter 22, this volume) have argued that the Southern-Superior Province boundary is an erosional feature and that originally it lay far to the north, and also that the Grenville Front Boundary Fault is much younger than the Sudbury Basin and hence that the proximity is meaningless in terms of the origin of the Sudbury Structure. The Ottawa-Bonnechère graben is also a later feature contained within the Grenville Province, and its significance to pre-Grenville features outside this province can only be assessed once the provenance of the Grenville has been established. Probably the most significant feature related to the Sudbury Structure is the thickening of the rocks of the Southern Province which occurs at and to the south of the Murray Fault System. This fault has played a major role in patterns and evolution of Early Proterozoic sedimentation, volcanism, plutonic activity, and deformation throughout the Southern Province.

It is the opinion of the present author, however, that the unique tectonic setting of the Sudbury Structure has been overemphasized, and that any attempt to locate a 60 by 40 km structure on a map of the Canadian Shield at random would produce an

equal number of apparently meaningful correlations with tectonic elements.

2. Peredery and Morrison (Chapter 22, this volume) have placed great emphasis on the Melt Bodies of the Onaping Formation being impact melts. The present author is impressed with the similarities between the matrices of these bodies and the Plagioclase-rich Granophyre that have been pointed out by Muir (Chapter 21, this volume) and suggests that further work is required on this problem, particularly trace element and isotopic work, to see if the matrices have distinctive composition, or if they can be modelled as variably contaminated granophyre.
3. Peredery (1972) and Peredery and Morrison (Chapter 22, this volume) have emphasized the heterogeneous nature of the recrystallized glass shards and flow-banded aphanitic rocks of the Onaping Formation, suggesting that this heterogeneity is more consistent with an origin as a result of the impact melting of a diversity of source rocks, than a volcanic origin. Muir (Chapter 21, this volume) has suggested that analyses of glasses that have recrystallized at a greenschist grade of metamorphism are unreliable indications of the original composition. This is certainly true, but the present author is impressed by the extreme range in composition found in closely associated fragments of glass from a single thin section. While the compositions may have been altered, it is unlikely that they have been greatly altered in such diametrically opposite directions in samples that must have experienced similar alteration histories. For this reason, Peredery and Morrison believe that the analyses are reasonable indications of the original compositions, and that the presence of such diverse melts, and the rarity of any volcanic material throughout so much of the Onaping Formation with any consistent composition, remains a point in favour of an impact origin.
4. Peredery and Morrison (Chapter 22, this volume) have argued that if the Onaping Formation is a series of ash or pyroclastic flows, as Muir (this volume) and others have suggested, it might be expected to contain examples of syn-emplacement welding. They claim that these are rare or absent; Muir (Chapter 21, this volume) claims the contrary. In this author's opinion, the degree to which the extent of the welding in the Onaping Formation either resembles or differs from that in ash or pyroclastic flows, as compared with suevite, remains to be established.
5. Plagioclase grains, 1 mm and more in diameter, occur both within the matrix and within former glassy material in the Onaping Formation. Presumably growth of these grains would take longer than the few seconds to minutes that they might exist in conjunction with a melt in a cloud of ejecta from an im-

compact crater. Peredery and Morrison (Chapter 22, this volume) interpret them as xenocrysts, pointing out that many are broken; Muir (Chapter 21, this volume) interprets some of them as phenocrysts, pointing out that many are not broken. It is difficult to form an opinion of the relative merits of the 2 viewpoints, given the current lack of quantitative information.

THIS AUTHOR'S OPINION

The greatest drawback to the interpretation of the Sudbury Structure as the result of impact remains the fact that it is not circular, and appears, on the basis of the available data, never to have been circular. The compositional stratification of the Onaping Formation and the presence within it of individual cooling units are also features with which proponents of impact have failed to come to grips. Recent work on the Vredefort structure, suggestive of an endogenous origin, is important new evidence weighing against an impact origin for Sudbury.

On the other hand, (1) the very unusual nature of the Sudbury Structure, (2) the similarity of the Sudbury Breccia and Gray Member (Onaping Formation) to the Ries pseudotachylite and suevite, respectively, and (3) the plethora of other breccias including the Footwall Breccia and the Basal Member (of the Onaping Formation), coupled with the evidence of an intense shock wave, all attesting to an enormous release of energy at Sudbury, indicate that an extremely unusual and catastrophic event occurred. We know that the impact of a large meteorite could produce many of the observed effects, and that many such impacts have occurred on earth. Our understanding of how an endogenous explosion could be triggered within or beneath the continental crust remains highly obscure.

For these reasons, the author regards the impact model as a reasonable working hypothesis. It is not proven; in fact, it rests on distinctly less certain ground than it did 15 years ago. Alternative hypotheses should definitely be kept in mind. Nevertheless, in the author's view, impact remains an attractive concept for the origin of the Sudbury Structure.

THE NATURE AND ORIGIN OF THE SUDBURY IGNEOUS COMPLEX

Units of the Complex and their Geological Relationships to One Another

The main units of the Complex include (1) the Sublayer, (2) the marginal Quartz-rich Norite of the South Range and Mafic Norite of the North Range, (3) the

South Range Norite and Felsic Norite, (4) the Quartz Gabbro, and (5) the Granophyre and Plagioclase-rich Granophyre. All except the Sublayer are included within the Main Mass of the Complex.

MAIN MASS

The marginal unit of the Complex on the South Range is the Quartz-rich Norite. In this unit, the quartz content increases progressively toward the outer contact over the outer 300 m. Naldrett and Hewins (Chapter 10, this volume) consider the possibility that this increase is the consequence of contamination, but note that the increase in quartz occurs as much where the Footwall is composed of SiO_2 -deficient "greenstone" as it does where it is composed of granitic rocks. This indicates that if contamination is involved, it is not *in situ* contamination. The increase in quartz is accompanied by an equally progressive decrease in the average $\text{Mg}/(\text{Mg} + \text{Fe})$ ratio of the pyroxenes. This decrease is due to the pyroxenes becoming progressively more strongly zoned, with $\text{Mg}/(\text{Mg} + \text{Fe})$ decreasing towards the edges of grains, while the cores retain a constant composition. These observations, coupled with a decrease in grain size towards the margins, led Naldrett and Hewins to interpret the outer part of the Quartz-rich Norite as a non-cumulus rock that crystallized essentially *in situ*. They interpret the South Range Norite as a cumulate, and the gradation between the two as the consequence of progressively less cumulus crystallization occurring toward the cooler outer margin of the intrusion.

On the North Range, the marginal phase is the Mafic Norite. This is very distinct from the South Range Quartz-rich Norite, in that it is significantly poorer in quartz, and is more primitive in terms of the $\text{Mg}/(\text{Mg} + \text{Fe})$ of its pyroxenes than any other phase of the Complex. The Mafic Norite is not gradational with the overlying Felsic Norite, but a break exists in the $\text{Mg}/(\text{Mg} + \text{Fe})$ of the pyroxenes, indicating that the magma responsible for the Felsic Norite was distinctly more fractionated than that responsible for the Mafic Norite. The introduction of new magma or the removal of a substantial thickness of cumulates is, therefore, indicated at this stage in the development of this part of the Complex.

Much of the material that is missing on the North Range between the Mafic and Felsic Norites appears to be present on the South Range as the South Range Norite. Variation in pyroxene compositions indicate that the South Range Norite becomes progressively more fractionated upward. The upper part of the South Range Norite is poorly preserved and no pyroxene analyses are available from it. However, on the basis of bulk composition, it is believed to be equivalent to the Felsic Norite. The Felsic Norite is better preserved and contains fresh pyroxene; a progressive iron-en-

richment has been documented in this pyroxene across the contact between the Felsic Norite and the overlying Quartz Gabbro.

Naldrett *et al.* (1970) have documented, on several traverses, the progressive change in mineralogy (including increase in the granophyric component of the rocks) that marks the transition of Quartz Gabbro into Granophyre. Hypotheses calling upon the introduction of a granophyre magma at a significantly later stage in the history of the Complex are not supported by the recognition of intrusive contacts. Peredery and Naldrett (1975) observed that large masses of a plagioclase-rich variant of the Granophyre occur either directly at the upper contact of the Complex, or just below this contact, enclosed within normal Granophyre. They note that if the normal Granophyre is removed from the section, the trends of major element variation, normative composition of plagioclase, and $Mg/(Mg + Fe)$ of pyroxene continue smoothly from the Quartz Gabbro into the Plagioclase-rich Granophyre. They suggested that the bulk of the Granophyre on the North Range is the consequence of a later introduction of magma along or close to the roof of the Complex. This magma may have been generated by differentiation, coupled with assimilation of roof rocks, near the centre of the Complex and then expelled laterally as structural readjustments lead to a subsidence at the centre. The lack of chilled contacts would suggest that this occurred while the Complex was still hot, probably while there was still some fractionated liquid preserved just beneath much of its upper contact.

SUBLAYER

The Sublayer occurs discontinuously around the Complex. It can be divided logically into those variants which occur close to the outer contact of the Complex (Naldrett *et al.*, Chapter 11, this volume) and those which occur within a series of dikes that radiate outward from the Complex and are known locally as offset dikes (Grant and Bite, Chapter 12, this volume).

Examples of the Contact Sublayer include the xenolithic norite and related gabbroic rocks which occur along the contact of the North Range. They are fine- to medium-grained rocks that can be distinguished from the Main Mass Felsic Norite and Quartz Gabbro by their lower quartz content in relation to pyroxene. Commonly they contain a suite of mafic and ultramafic inclusions. A medium-grained, generally inclusion-free variant has been called 'Pyroxene Sublayer' by Pattison (1979). It is found on both the North and South Ranges, generally between the Main Mass and the Footwall or between the Main Mass and other types of Sublayer. 'Basal Norite' is a coarse-grained, inclusion- and sulphide-bearing rock that is found along the base of the Complex on the South Range. It

is gradational upward into the Main Mass; some workers regard it as part of the Main Mass, while others regard it as Sublayer with a gradational contact.

Sublayer rocks occurring within the offset dikes generally have the composition of quartz diorite and are referred to as such. Grant and Bite (Chapter 12, this volume) recognize a number of variants of Quartz Diorite which form a continuum. At one end is Hypersthene Quartz Diorite, a medium- to coarse-grained, acicular hypersthene-bearing rock containing smaller grains of plagioclase, and interstitial quartz, orthoclase, granophyre, and biotite. With increasing amounts of amphibole and biotite, this grades into Amphibole Quartz Diorite. Much of the amphibole is after pyroxene, although Naldrett (1969) suggested that replacement and overgrowth by amphibole occurred at the magmatic stage. A decrease in amphibole and increase in biotite leads to Biotite Quartz Diorite, a change that is attributed to contamination. The extreme end-products of contamination are the granophyric and quartz-rich variants which are referred to as 'Contaminated' Quartz Diorite. One unusual variant that is found at the distal end of the Copper Cliff Offset Dike is a biotite-free, amphibole-bearing, quartz-poor Quartz Diorite that Grant and Bite (Chapter 12, this volume) regard as an early differentiate. Later in this section, this rock is discussed again, and it is pointed out that there is little in its composition to support it being an early differentiate, but that it does appear to be less contaminated than most varieties of Quartz Diorite.

Geological relationships between the Sublayer and the Main Mass that bear on the relative ages of the two are conflicting. Naldrett *et al.* (Chapter 11, this volume) describe Sublayer rock that cuts Main Mass norite and that contains inclusions of this norite and of other varieties of Sublayer, in which the inclusions are oriented parallel to the contact with the norite. This is not mineralized Sublayer, which Naldrett *et al.* (Chapter 11, this volume) report to be older than the unmineralized variant, although they have no evidence bearing on the age of the mineralized material relative to the Main Mass. Grant and Bite (Chapter 12, this volume) report rounded inclusions of mafic rock, up to 2 m in diameter, which are mineralogically and texturally similar to basal norite, in Quartz Diorite at the Worthington and Copper Cliff Offset Dikes. Davis *et al.* (Chapter 16, this volume) describe angular inclusions of sulphide-bearing Quartz-rich Norite in Sublayer norite at Little Stobie Mine. Naldrett *et al.* (1972) reported inclusions of Mafic Norite in Footwall Breccia near the Strathcona Mine on the North Range, where Sublayer Xenolithic Norite intervenes between the two. This occurrence is easier to explain if the Sublayer is the younger rock. The alternative explanation that the breccia has been injected, together with its Mafic Norite inclusions, into position beneath the

Sublayer is less likely since there is no alignment of inclusions or other flow lines within it suggestive of movement.

On the other hand, Pattison (1979) pointed to the manner in which the Sublayer fills radial fractures in the Footwall. He argued that the fractures were probably related to the catastrophic event at Sudbury; if this were true, the earliest intrusions would be expected to fill them, indicating that the Sublayer predated the Main Mass. He also argued that the geometry of the offset dikes and embayments filled by Sublayer, which project into the Footwall but never cut back into the Main Mass, is suggestive that the Main Mass was injected later than, and above the Sublayer, planing off irregularities along the Sublayer upper contact. He pointed out that inclusions of Sublayer and massive Ni-Cu sulphide have been observed in the Main Mass norite, citing an inclusion in mineralized Main Mass norite at Little Stobie Mine. Since Pattison's work, Muir (1981) has described Sublayer back-intruding Main Mass norite on the North Range, and Dressler (1982) has described similar occurrences on the South Range. The vertical section of the Strathcona deposit presented by Naldrett and Kullerud (1967) shows Sublayer apparently cutting Main Mass norites. Nevertheless, the discordance of the Sublayer with the Footwall rocks is very much more pronounced than it is with those of the Main Mass.

Slaught (1951) has documented a gradation from basal Main Mass norite into Quartz Diorite within the Copper Cliff Offset Dike.

The field evidence is therefore contradictory, not supporting an undisputed earlier or later age for the Sublayer. Contacts are never marked by fine-grained chill zones, suggesting that whichever was the older at any particular location, it was still warm at the time of intrusion of the younger. On the North Range, the distinction between Main Mass and Sublayer is always clear with the Sublayer having the finer grain size and lower quartz content. This is not always the case on the South Range, where a number of authors have commented on gradations that are visible between the two.

PALEOMAGNETIC EVIDENCE

Morris (this volume) has identified 3 principal magnetic remanence directions developed within the Main Mass of the Sudbury Igneous Complex which he names Types 1, 2, and 8. Type 1 is restricted to the norite, Type 2 is found in both norite and Granophyre, while Type 8 is restricted to the Granophyre.

As discussed previously, Types 1 and 2 record a 2-stage inward steepening of dips around much of the Complex. They are supported by contact tests, and provide strong support for the model that emplacement of much of the Granophyre postdated that of

much of the norite, with subsidence occurring at the centre of the structure both after initial emplacement of the norite and following emplacement of both units.

Type 8 does not reflect the inward steepening of dips, and therefore, postdates the subsidence. It is not supported by a contact test, and therefore, could reflect a metamorphic rather than an intrusive event. Morris (this volume) points out that it is not present in either the underlying norite or the overlying Onaping Formation. He argues that if it was a metamorphic event, it was a peculiar one, restricted to the Granophyre, and therefore, interprets it as due to a second, late stage introduction of Granophyre. He speculates that this may be very much later than the bulk of the Sudbury Igneous Complex, possibly corresponding to Gibbins and McNutt's (1975) radiometric age of 1.591 ± 0.13 Ga. Naldrett *et al.* (1970) described a metamorphism that was restricted to the Granophyre and upper part of the Quartz Gabbro. This involved saussuritization of plagioclase to produce quartz and albite and also the formation of stilpnomelane and the alteration of pyroxene. Naldrett *et al.* (1970) interpreted it as an 'auto-retrogressive' reaction, brought about by the build up of H_2O in the upper part of the Complex as it crystallized. The present author believes that the Type 8 remanent magnetization is related to this alteration, and that the postulate of a second, much later injection of Granophyre is not warranted by either the available paleomagnetic or field data.

Morris' (Chapter 19, this volume) Type 3 remanence directions are associated with the mineralization at Sudbury, as are some of his Type 8 directions. The present author has some reservations about interpreting these data in terms of the initial development of the Sudbury Structure, since they are based on sulphide samples. Sulphides are highly susceptible to exsolution and alteration at low temperature. It is not clear to what extent these factors may have influenced fixation of the remanent magnetization directions.

ISOTOPIC EVIDENCE

Krogh *et al.* (Chapter 20, this volume) report the results of Pb-U radiometric dating of the Mafic, Felsic, and South Range Norites and the Granophyre. All of their dating of the noritic rocks is consistent with an age of $1.85 \text{ Ga} \pm 0.001$ and they conclude that within the errors of their technique (about 10^6 years at Sudbury) all of the units are coeval. Baddeleyite from 1 sample of Plagioclase-rich Granophyre also gave an age of 1.85 Ga and it would seem that this unit is coeval with the others.

Krogh *et al.* (Chapter 20, this volume) discuss previous attempts at dating using Sr^{87}/Sr^{86} methods in the light of their own very precise measurements, and conclude that the rocks have not behaved as entirely

TABLE 25.3: COMPARISON OF MAJOR ELEMENTS OF ROCKS OF SUDBURY IGNEOUS COMPLEX.

	OFFSET ROCKS			MAIN MASS						FLOOD BASALTS				BUSHVELD	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
	Quartz poor Offset (SR)	Typical Offset (SR)	Offset (NR)	Quartz-rich Norite (SR)		South Range Norite	Felsic Norite	Quartz Gabbro	Grano- phyre	Keweenaw Basalt	Columbia Basalt	Keweenaw Basalt	Columbia Basalt	Norite	
SiO ₂	50.7	55.3	61.5	56.7	57.0	55.4	60.4	58.9	68.1	49.1	48.7	50.0	48.9	53.3	
TiO ₂	1.56	0.94	0.73	0.57	1.34	0.49	0.65	1.62	0.65	1.89	2.73	0.99	0.96	0.19	
Al ₂ O ₃	16.3	14.3	14.9	16.3	16.4	17.8	15.6	13.5	13.7	16.80	16.4	16.3	17.0	19.2	
FeO ^r	11.4	10.8	6.84	7.44	7.33	7.35	7.19	10.5	5.21	11.91	12.5	9.78	10.0	7.60	
MnO	0.17	0.15	0.11	0.12	0.13	0.12	0.13	0.14	0.09	0.17	0.18	0.18	0.20	0.16	
MgO	4.91	4.43	3.82	6.10	6.40	6.68	3.91	2.66	1.08	6.61	5.45	8.08	7.90	7.34	
CaO	7.92	6.71	4.70	6.66	7.28	7.75	6.05	5.48	2.15	10.03	8.7	11.1	11.1	10.0	
Na ₂ O	2.76	2.61	3.15	—	2.41	2.50	3.12	3.13	3.31	2.76	3.34	2.52	2.49	2.95	
K ₂ O	1.66	1.70	2.60	1.40	1.55	1.10	1.96	2.13	5.00	0.52	0.91	0.43	0.28	0.38	
Total	97.28	96.9	98.4	—	99.84	99.2	98.90	98.06	99.29	98.79	98.97	99.38	98.53	101.12	
Mg/No	0.43	0.42	0.50	0.59	0.61	0.62	0.47	0.31	0.27	0.50	0.44	0.60	0.59	0.63	
Na ₂ O/K ₂ O wt. %	1.76	1.54	1.21	—	1.56	2.27	1.59	1.47	0.66	5.31	3.67	5.86	8.89	7.76	

Explanation to Table 25.3

1. Grant and Bite (Chapter 12, this volume) Table 12.2, No. 4 (Average of 4)
 2. Grant and Bite (Chapter 12, this volume) Table 12.2, No. 2 (Average of 14)
 3. Grant and Bite (Chapter 12, this volume) Table 12.2, No. 5 (Average of 17)
 4. Grant and Bite (Chapter 12, this volume) Table 12.2, No. 6 (Average of 31)
 5. Collins (1934) P. 140 No. 92 W
 6. Collins (1934) P. 140 No. 89 W
 7. Grant and Bite (Chapter 12, this volume) Table II, No. 9 (Average of 31)
- FeO^r = Total Fe calculated as FeO
Mg/No = Mg/(Mg + Fe) atomic

8. Grant and Bite (Chapter 12, this volume) Table II, No. 10 (Average of 17)

9. Collins (1934) P. 139 No. 56 W

10. Transitional Basalt, Basaltic Volcanism Study Project (1981) Table 1.2.2.19 No. KEW 4

11. Basalt, Basaltic Volcanism Study Project (1981) Table 1.2.3.4 No. CP-4

12. Olivine Basalt, Basaltic Volcanism Study Project (1981) Table 1.2.2.19 No. KEW-8

13. Olivine Basalt, Basaltic Volcanism Study Project (1981) Table 1.2.2.4 No. CP-3

14. Naldrett, unpublished data.

closed systems for Sr and Rb, resulting in apparent age differentials such as that observed by Gibbins and McNutt (1975) who obtained 1.915 ± 0.098 Ga for the norites and 1.645 ± 0.062 Ga for the Granophyre.

Krogh *et al.* have not dated the normal Granophyre, which Peredery and Naldrett (1975) have interpreted as having been emplaced slightly after the Plagioclase-rich Granophyre. However, there is no field evidence to suggest that the time difference in the intrusion of these 2 units is appreciable in comparison with the time required for the Complex to cool.

Geochemistry of the Sudbury Igneous Complex

MAJOR ELEMENTS

A selection of average and individual major element analyses of representative material from the Sudbury Igneous Complex are listed in Table 25.3. These are drawn from this volume and elsewhere. Other analyses can be found in Grant and Bite (Chapter 12, this volume) Table 12.2 and Naldrett *et al.* (Chapter 11, this volume) Table 11.1.

Main Mass

Judging from field and petrographic criteria, the Quartz-rich Norite is the rock type that is likely to have been closest to the composition of the Sudbury Igneous Complex magma when it was emplaced along the South Range. Two analyses of this are given in Table 25.3; No 4 is Grant and Bite's (Chapter 12, this volume) average of 31 samples, but is lacking in Na_2O ; No 5 is one of Collins' (1934) analyses that was chosen to be closest in SiO_2 to No. 4. The $\text{Mg}/(\text{Mg} + \text{Fe})$ atomic ratio (henceforth referred to as MgNo) of 0.61 indicates that this is a fairly primitive rock.

Since the Sudbury Igneous Complex is an example of continental tholeiitic magmatism, continental flood basalts provide one of the best yardsticks with which to compare it. In Figure 25.3, the Quartz-rich Norite is compared with Keweenaw and Columbia River flood basalts on the basis of their MgNos. The high SiO_2 and K_2O , low CaO and low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio of the Quartz-rich Norite when compared with flood basalts of similar MgNo is very obvious. The characteristics of high SiO_2 and K_2O and low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ extend to the cumulus rocks, as a comparison of analysis 6, Table 25.3 (South Range Norite) with analysis 14 (typical Bushveld norite) shows. Some caution is necessary with regard to the comparison, since with cumulates the proportion of trapped intercumulus liquid is a complicating factor, an increase in the proportion tending to raise both SiO_2 and K_2O . The siliceous nature of the Complex has already been discussed by Naldrett and Hewins (Chapter 10, this volume) who

suggest contamination as the cause. Contamination of a relatively unfractionated Columbia River basalt (analysis 4, Table 25.4) with 50% of a 1:2 mixture respectively of Archean quartz monzonite and gneiss (column 3, Table 25.4) gives rise to the composition listed in column 6, Table 25.4. This is quite similar, considering the arbitrary manner of choosing the end members, to Collins' sample of Quartz-rich Norite (column 7, Table 25.4). As discussed by Rao *et al.* (1983), any real process of contamination is likely to be more complex than this, with crystallization accompanying assimilation. However, the conclusion on the basis of the major elements is that contamination of the Sudbury Igneous Complex magma by felsic country rocks is permissible, in fact even likely.

Sublayer

It is argued by Naldrett *et al.* (Chapter 11, this volume) that the texture and field relations of various units of the Sublayer suggest that these are also not cumulates, but are rocks that have solidified essentially *in situ*, and thus represent magma compositions. Ac-

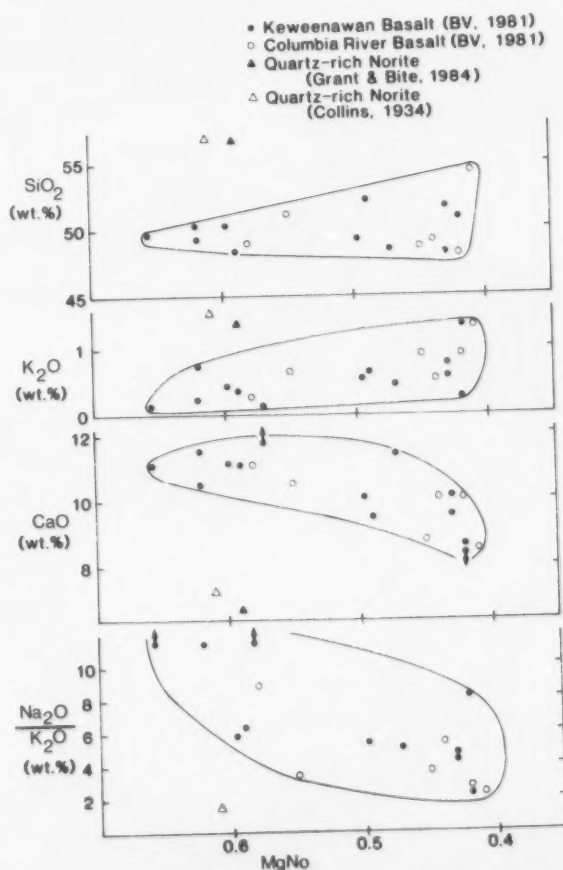


Figure 25.3. Comparison of some major element concentrations in the Quartz-rich Norite with those in typical continental flood basalts.

TABLE 25.4: COMPOSITIONS RELATING TO THE CONTAMINATION OF THE SUDBURY IGNEOUS COMPLEX MAGMAS.

	1	2	3	4	5	6	7	8	9
Major Elements Weight %									
SiO ₂	70.4	64.8	66.7	48.9	49.1	57.8	57.0	53.5	51.7
TiO ₂	0.46	0.78	0.67	0.96	1.89	0.82	1.34	1.59	1.31
Al ₂ O ₃	15.6	16.2	16.0	17.0	16.80	16.5	16.4	16.6	14.7
FeO	2.2	4.35	3.63	10.0	11.91	6.81	7.83	9.84	12.84
MgO	0.73	2.43	1.86	7.9	6.61	4.88	6.46	5.42	6.21
CaO	1.96	3.48	2.97	11.1	10.03	7.04	7.28	8.27	9.52
Na ₂ O	3.93	3.89	3.90	2.49	2.76	3.20	2.41	3.05	2.81
K ₂ O	3.33	1.80	2.31	0.28	0.52	1.30	1.55	0.97	0.81
Trace Elements ppm									
La	—	—	—	6.77	15.2	—	—	—	18.0
Ce	97.9	83.8	89	16.0	33.5	52.3	57.6	47.4	48.2
Nd	31.	37.2	35.1	—	—	—	26.8	—	17.8
Sm	4.55	6.57	5.9	2.72	4.80	4.31	4.52	5.08	4.65
Eu	0.89	1.66	1.37	1.03	1.58	1.20	1.26	1.53	1.96
Gd	2.88	4.79	4.15	3.18 ⁽ⁱ⁾	4.8 ⁽ⁱ⁾	3.67	4.13	4.64	4.60 ⁽ⁱ⁾
Tb	—	—	—	0.59	0.83	—	0.56	—	0.76
Yb	0.696	1.20	1.03	2.20	2.35	1.62	1.88	2.02	1.43
Lu	—	—	—	0.33	0.36	—	—	—	0.27
Ba	807	992	930	180	—	555	—	—	—
Rb	166	75.9	106	2.3	10	54	—	34	21
Sr	290	753	599	338	284	469	—	362	602
Mg/No	—	—	0.477	0.585	0.497	0.56	0.611	0.495	0.463
K/Rb	—	—	—	—	—	—	—	—	—
Rb/Sr	—	—	0.18	0.007	0.035	0.115	—	0.094	0.035
Sc/Ba	—	—	0.64	1.88	—	0.85	—	—	—
Ce/Yb	—	—	—	—	—	—	—	—	—

Explanation to Table 25.4

1. Average 'Granite' from Table 25.1

Trace elements are of Archean quartz monzonite with very similar major element composition from Arth and Hanson (1975) Table 2, Analysis 29.

2. Average Gneiss from Table 25.1

Trace elements are of tonalitic gneiss of similar major element composition from Arth and Hanson (1975) Table 2, Analyses 22.

3. Mixture of 1 and 2 in the proportion 1:2.

4. Relatively primitive continental flood basalt from Columbia River Province, Basaltic Volcanism Study Project (1981) Tables 1.2.3.4 and 1.2.3.5 analysis no. CP-3 (calculated on volatile-free basis).

5. Moderately fractionated continental flood basalt from Keweenaw Province, Basaltic Volcanism Study Project (1981) Tables 1.2.2.19, 1.2.2.22 and 1.2.2.23, analysis no. KEW-4 (calculated on volatile-free basis).

6. Calculated composition of South Range initial magma combining columns 3 and 4 in the proportions 1:1.

7. Composition of marginal Quartz-rich Norite (Table 25.3, Analysis 5) for comparison with column 6.

8. Calculated composition of a relatively primitive sublayer magma, combining columns 3 and 5 in the proportions 1:3.

9. Composition of one of the least fractionated North Range Sublayer samples from Rao *et al.* (1983) Tables 1 and 3, Analysis BVR-11.

All analyses calculated on a volatile-free basis.

FeO* = Fe calculated as FeO

Mg/No = Mg/(Mg + Fe) atomic ratio.

(i) = chondrite normalized Gd for these two samples assumed to be the weighted average of 2 parts of Tb and 1 part of Sm, all on a chondrite normalized basis.

cepting this premise, the MgNos become important indices of the degree of fractionation of the rocks and therefore of the magmas. MgNos of North Range samples of Contact (as opposed to Offset) Sublayer given in Table 11.1 vary from 0.42 to 0.50, with most in the range 0.45 to 0.50 and with an average of 0.47; those from the South Range vary from 0.37 to 0.58 with most in the range 0.49 to 0.58 and with an average of 0.51. Thus the magmas are relatively fractionated,

considerably more so than the Main Mass as represented by the Quartz-rich Norite. At the same time, the MgNos indicate a variable degree of fractionation for different samples of the Sublayer.

Comparison of the major element concentrations (Figure 25.4) of Sublayer with those of flood basalts indicates that the Sublayer is also enriched in SiO₂ and K₂O, and low in CaO and Na₂O/K₂O ratio for a given

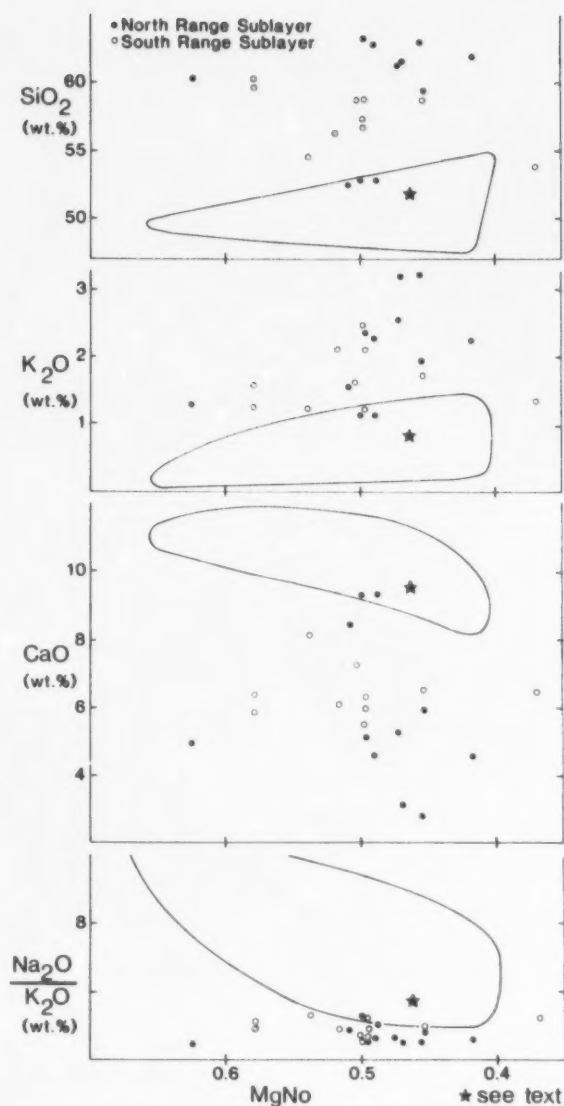


Figure 25.4. Comparison of some major element concentrations in the Sublayer with those in typical continental flood basalts.

degree of fractionation as indicated by the MgNo. Contamination by country rocks is therefore indicated by the data.

Grant and Bite (Chapter 12, this volume) give analyses of Offset Sublayer, some of which are reproduced in Table 25.3. It is seen from the MgNos that these are some of the most fractionated examples of the Sublayer, but that the spread in MgNo is much less than is the case for the Contact Sublayer. Grant and Bite point to 1 sample representative of rather quartz-poor rocks that occur at the distal end of the Copper Cliff Offset Dike, reproduced in Table 25.3 as analysis 1. This has a low MgNo and a fairly low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio. It is, however, much poorer in SiO_2 than other rocks within the offset dike, and they suggest that it may rep-

resent an early magma, perhaps one from which the other rocks were derived by contamination. The offset dike cuts arkosic and gabbroic rocks and, prior to the introduction of the Quartz Diorite that currently fills part of it, appears originally to have contained Sudbury Breccia with a matrix probably close in composition to that listed in Table 25.1 as being characteristic for parts of offset dikes with arkosic and gabbroic country rocks. A 'petmix'² mixing calculation was performed, and the results indicate that the closest approximation to a typical sample from the Copper Cliff Offset Dike is obtained (calculation 1, Table 25.5) when 60.4% of the distal variety of the Quartz Diorite is combined with 24.7% of gabbro-type matrix and 10.6% of arkose-type. A similar calculation performed to model the Offset Dike rock of the North Range (analysis 3, Table 25.3) indicates (calculation 2, Table 25.5) that if 23.2% of the distal Copper Cliff Quartz Diorite is combined with 76.8% of the breccia matrix found in gneiss; a reasonable similarity with the North Range Offset Dike rock is produced.

Thus, the major element compositional range of the Offset Dike rocks can be explained by the incorporation of variable amounts of Sudbury Breccia matrix. The mechanism by which large amounts of contaminants can be incorporated by mafic magma is not clear. Possibly, the contamination is a multi-stage process, with magma containing a certain proportion of pulverized country rock becoming heated by proximity to the Main Mass of the Sudbury Igneous Complex and thus liquified, after which it incorporates more material and the process is repeated. Perhaps the passage of fresh, hot magma along the length of an offset dike provides heat to assist early, marginal phases of the intrusion in assimilating the breccia matrix with which they have come in contact. What is clear from both the field relations and the available chemical data is that the large increases in SiO_2 and alkalis that mark the Quartz Diorites of the offset dikes, where they come into contact with country rocks, is not primarily due to fractionation (the MgNos do not change) but can be accounted for by assimilation.

Naldrett *et al.*'s (Chapter 11, this volume) data on the Contact Sublayer indicate a wider range of MgNos than that characteristic of the Offset Sublayer, and Rao *et al.* (1983) have shown that fractional crystallization in addition to assimilation is required to explain the observed compositional variations. Analysis 9 (BVR-11) in Table 25.4 (indicated by a star in Figure 25.4) is one of the more primitive of the North Range samples ex-

²Petmix is essentially a 'least squares' technique to calculate the optimum proportions in which to mix a number of compositions in order to achieve a specific end product. It is a modification of the program of Wright and Doherty (1970) by M.J. Gorton (Department of Geology, University of Toronto, personal communication, 1984).

TABLE 25.5: 'PETMIX' MODELLING OF QUARTZ DIORITE OF THE OFFSETS.

	Calculation of Composition 1	Observed	Calculation of Composition 2	Observed
SiO ₂	55.6	55.3	60.5	61.5
TiO ₂	1.40	0.94	1.05	1.08
Al ₂ O ₃	15.9	14.3	15.1	15.6
FeO	10.2	10.8	7.41	7.63
MgO	4.7	4.4	3.15	3.82
CaO	6.8	6.7	4.64	4.70
Na ₂ O	2.42	2.61	3.67	3.15
K ₂ O	1.81	1.70	1.50	2.60

Calculation 1 = 60.4% of (Analysis 1, Table 25.3) plus 24.7% of (Analysis 8, Table 25.1) plus 10.6% of (Analysis 10, Table XX.2.1).

Calculation 2 = 23.2% of (Analysis 1, Table 25.3) plus 76.8% of (Analysis 2, Table 25.1).

amined by Rao *et al.* (1983). In its major element composition and Na₂O/K₂O ratio of 3.47, it is not unlike some of the more fractionated flood basalts. However, its trace element composition is different, as is discussed below.

TRACE ELEMENTS

Data for trace elements in the Sudbury Igneous Complex are much less abundant in the literature than are those for major elements. Data exist for rare earth elements (REE) on most units of the Complex, but that of Rao *et al.* (1983) on the Sublayer is all that is available in the way of modern determinations of other incompatible trace elements.

In Figure 25.5, Kuo and Crockett's (1979) REE pattern for the Quartz-rich Norite is compared with those for the 2 flood basalts samples of similar MgNo that have been discussed above. The much steeper slope of the Sudbury samples (La/Yb = 17) as compared to the flood basalts (La/Yb = 3) is obvious.

The range of REE patterns for the Sublayer of the Sudbury Igneous Complex, together with the averages for the North and South Ranges are compared with flood basalts of similar MgNo in Figure 25.6. The Sublayer patterns, with their La/Yb ratios of 16, are essentially identical in slope and magnitude to the av-

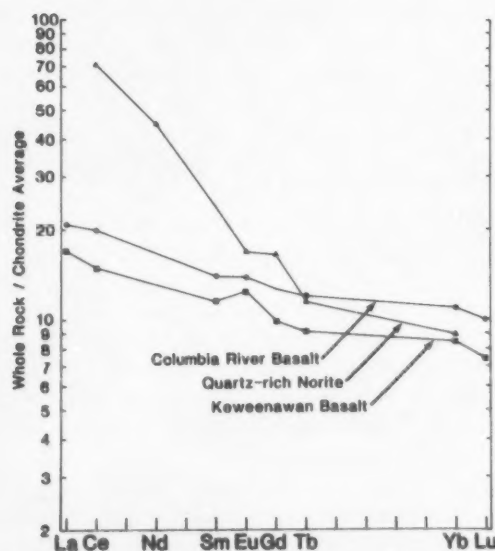


Figure 25.5. Comparison of REE data for the Quartz-rich Norite (from Kuo and Crockett 1979) with that for a Keweenaw and a Columbia River flood basalt of similar MgNo.

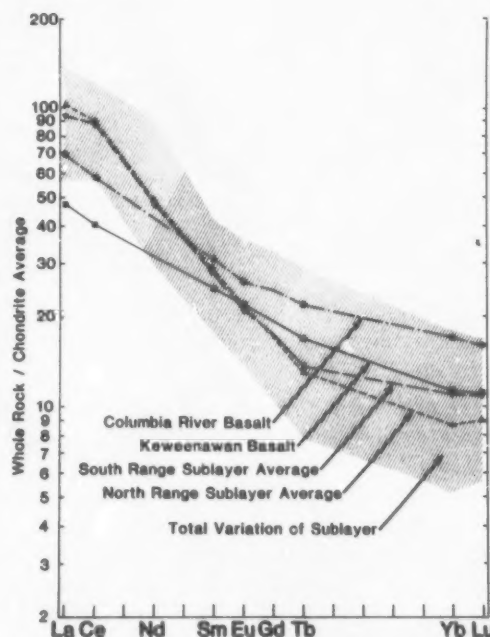


Figure 25.6. Comparison of REE data for the Sublayer with that for relatively fractionated Keweenaw and Columbia River basalts.

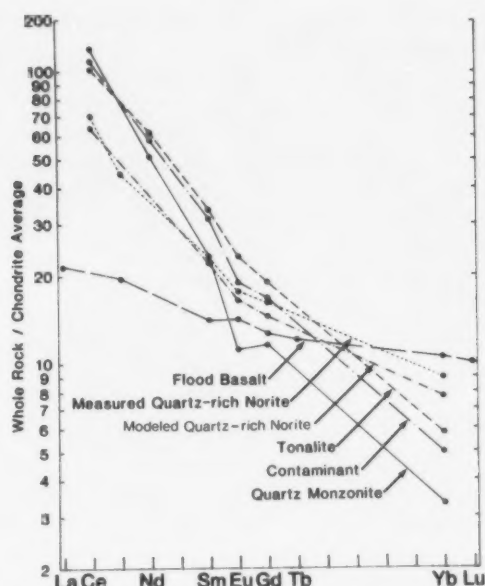


Figure 25.7. REE data relating to the mixing of Archean tonalitic gneiss and quartz monzonite with relatively unfractionated Columbia River basalt to produce a composition similar to the Quartz-rich Norite.

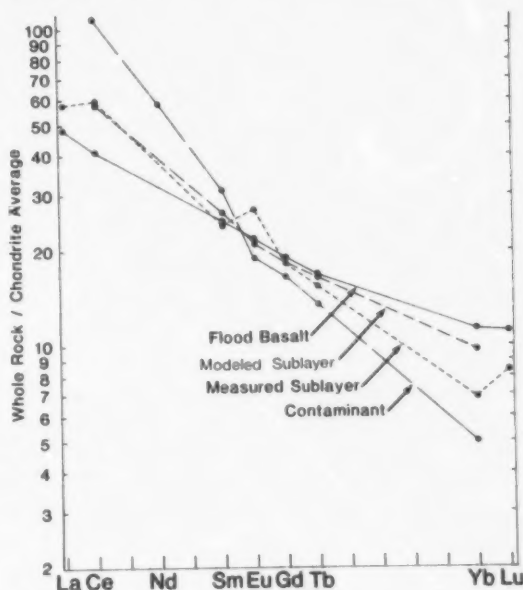


Figure 25.8. REE data relating to the mixing of Archean tonalitic gneiss and quartz monzonite with a relatively fractionated Keweenaw basalt to produce a composition similar to one of the least contaminated samples of the Sublayer.

erage pattern for the Quartz-rich Norite and, again, are very much steeper than those of the flood basalts ($\text{La}/\text{Yb} = 6$).

The LREE enrichment of the Sudbury rocks could be attributed to contamination by LREE-enriched country rocks. One feature of the Sudbury patterns is

the absence of a Eu anomaly. This would preclude contamination by granite or quartz monzonite with their characteristic negative Eu anomalies. Tonalitic gneisses typically are enriched in LREE and show no Eu anomalies (Arth and Hanson 1975), so that they are a possible contaminant. However, they cannot account for the low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of the Sudbury rocks.

A representative set of trace element data for the country rocks of the Sudbury area are not available. However, Arth and Hansen (1975) have investigated the tonalitic gneisses, quartz monzonites, and other rocks of the Archean of northeastern Minnesota. Their quartz monzonites bear a close resemblance in major element composition to the average Sudbury Archean 'granite' listed in Table 25.1, while some of their tonalites closely resemble the average 'gneiss' listed in the same table. In Table 25.4 and Figure 25.7, an investigation of the effect of contamination by a mixture of gneiss and granite is attempted, using the major element data from Table 25.1 and trace element data from Arth and Hansen (1975). It is found that a 1:2 mixture respectively of granite and gneiss provides a reasonable contaminant (Table 25.4, column 3) in which the Eu anomaly of the granite is effectively diluted by the contribution from the gneiss. The close similarity between the product of linear 1:1 mixing of this mixture with the Columbia River basalt referenced above (column 4, Table 25.4) and Quartz-rich Norite is shown for the REE in Figure 25.7.

Column 8 of Table 25.4 is an attempt to model one of the least contaminated of Rao *et al.*'s (1983) Contact Sublayer samples (BVR-11), given in column 9, by mixing 25% of the postulated granite-gneiss contaminant with 75% of a relatively fractionated Keweenaw basalt, listed in column 5. The match is reasonable, although MgO , CaO , and particularly FeO are low, and Al_2O_3 and SiO_2 are high. The REE pattern (Figure 25.8) indicates a close match, except that the model composition does not show the positive Eu anomaly of BVR-11. (This positive Eu anomaly is atypical of the Sublayer, very few other Sublayer samples show it). Rao *et al.* emphasize that the majority of their Sublayer samples are best modelled as the consequence of the fractionation of the more primitive variants, such as BVR-11, coupled with assimilation of country rocks. From the above discussion, particularly that with reference to the REE profiles, even the more primitive Sublayer material seems to have been contaminated to some extent, although this early contamination has been less intense than that which affected the initial magma of the Main Mass.

ISOTOPES

Krogh *et al.* (Chapter 20, this volume) have shown from Pb-U radiometric dating of zircons and badde-

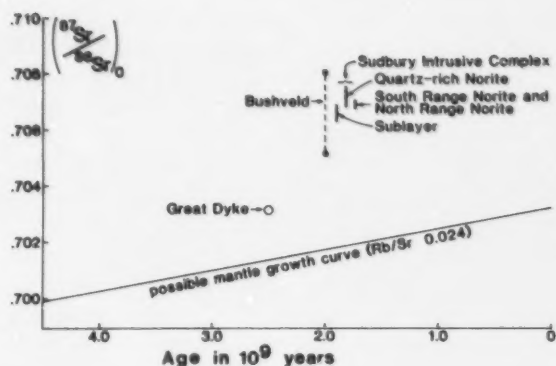


Figure 25.9. Sr initial ratios for rocks of the Sudbury Igneous Complex compared with those of other large layered intrusions and a possible mantle growth line.

leyite that the Sudbury Igneous Complex has an age of 1.85 Ga. A value for the decay constant for Rb^{87} of $1.42 \times 10^{-11} a^{-1}$ and a model age of 1.85 Ga has been used to recalculate the initial Sr^{87}/Sr^{86} ratios for the data of Gibbins and McNutt (1975). The average and range for a number of units of the Complex are shown in Figure 25.9 compared on the basis of age with data for a number of other layered intrusions, and with a hypothetical mantle growth line. While Sudbury is not unique in having high $(Sr^{87}/Sr^{86})_0$ ratios for its age, these values suggest nevertheless either the incorporation of radiogenic strontium into the primary Sudbury Igneous Complex magma, through interaction with country rocks, or derivation of the primary magma from a part of the mantle that contained very radiogenic strontium. Values for the Sublayer cover a wider range, but are somewhat lower than those for the Main Mass norites. This suggests that, if contamination was involved, the Main Mass was affected more consistently and to a greater degree than the Sublayer.

Ding and Schwarcz (in press) pointed out that their oxygen isotope data are consistent with the contamination of the Main Mass magma by Footwall gneiss as found on the North Range, but that the ratios are also similar to those of other continental volcanic rocks and, therefore, do not prove contamination. The somewhat higher ratios of the South Range Norite are also compatible with the hypothesis that the McKim Formation greywackes from the country rocks to the South Range have been assimilated, but once again the ratios of the norite are within that observed in primitive, uncontaminated magmas.

Summary of Petrology

Field relations and radiometric data indicate no substantial age difference between any of the Sudbury Igneous Complex rocks, including the Sublayer, Main

Mass norites, and Granophyre. The unusually quartz-rich composition of the Complex relative to $Mg/(Mg + Fe)$ ratio of its pyroxenes, and the LREE enrichment and the low Na_2O/K_2O ratios shown by all units are anomalous relative to other layered mafic complexes. The existence of these features in rocks believed to be close to original magma compositions is also anomalous with respect to continental basalts.

The composition of the border facies of the Sudbury Igneous Complex can be modelled in a crude sense by combining 50% of a relatively primitive continental flood basalt with 50% of a mixture of basement tonalitic gneiss and quartz monzonite. Oxygen isotope ratios are consistent with contamination of this kind, which also provides an explanation for the high Sr initial ratios which characterize the Complex.

Paleomagnetic data suggest that after initial emplacement of the noritic rocks, subsidence occurred at the centre of the Complex, steepening the dip of the Footwall by 10° to 40° . Following this, granophyre spread out over the top of the noritic rocks and solidified. Subsequent deformation steepened dips along the South Range by a further 30° .

Field relations bearing on the age of the Sublayer indicate that it may be slightly older, slightly younger, or, in some cases, contemporaneous with and grading into the Main Mass. Major element data indicate that the Sublayer is more fractionated than the initial magma of the Main Mass, and that it has been contaminated to a lesser extent. This is borne out also in the $(Sr^{87}/Sr^{86})_0$ ratios. Major and trace element variation within the Contact Sublayer are explicable in terms of simultaneous crystallization and assimilation. The Offset Sublayer has become highly contaminated, probably by crushed and pulverized country rocks that filled the offset dikes when the Sublayer was injected along them.

All of these features are used to constrain the model for the development of the Sudbury Igneous Complex which is presented at the end of this chapter.

ORIGIN AND EVOLUTION OF THE Ni-Cu ORES

Types of Ore Deposits

The Ni-Cu ores at Sudbury occur around much of the outer perimeter of the Sudbury Igneous Complex and are sub-divisible into a number of distinctive types, separable into 2 broad groupings:

Contact Deposits

- (1) North Range deposits
- (2) South Range deposits
- (3) Fault-controlled deposits
- (4) Others

Offset Deposits

- (1) Normal type
- (2) Frood-Stobie

This summary will focus on the most important of these types, namely the North and South Range deposits and those of the Offset Dikes. Brief descriptions of the fault-controlled, Frood-Stobie and some other types are given by Naldrett (this volume).

NORTH RANGE DEPOSITS

Much of the Footwall of the North Range is characterized by a mega-breccia which extends up to several 100s m away from the contact (Coats and Snajdr, Chapter 14, this volume; Morrison, Chapter 23, this volume). More finely brecciated zones occur within and peripheral to the mega-breccia and are known as Sudbury Breccia (Dressler, Chapter 6, this volume). Ore deposits occur along much of the perimeter of the North Range, but are particularly common over the part from Hardy Mine east to Longvack. Coats and Snajdr (Chapter 14, this volume) report that the Fecunis Lake Fault, at about the centre of this section, is a natural dividing line. East of the fault, all of the deposits are related to a trough-like depression in the Footwall (the Strathcona embayment). This outcrops at Longvack and plunges to the west at 22° for approximately 3 km, before levelling out and continuing at depth horizontally to the fault. The trough is approximately 600 m wide and 350 m deep. It is lined with finely brecciated Footwall material (the Footwall Breccia) and is also marked by a thickening in the Sublayer and Main Mass norites. West of the Fecunis Fault, several trough-like depressions in the Footwall display many of the features of the Strathcona embayment but lack the overall continuity.

Morrison (Chapter 23, this volume) emphasizes the importance of radially oriented troughs around the Sudbury Structure as locii for mineralization. Morrison equates them with the troughs which mark the lines of intersection of the sides of polygonally shaped lunar craters. At Sudbury, irregularities in the dip of the Footwall are termed embayments, and are often the locii for ore deposits, particularly so (according to Morrison) when they are associated with troughs. Some troughs, such as those at Whistle, Trilabelle, and Copper Cliff, are clear on a map of the Sudbury Structure, usually with Offset Dikes associated with them. Others referenced or implied by Morrison are not so clear on the surface map. There does, however, appear to be an association of ore deposits with the locii of troughs as predicted by Morrison in his Figure 23.3.

The Levack Number 4 orebody (Morrison, Chapter 23, this volume, Figures 23.7 and 23.8) is typical of the North Range. The Footwall consists of a mega-breccia, cut by dikes and irregular masses of

Sudbury Breccia. This is overlain by the Footwall Breccia, composed of fragments of Footwall rocks in a matrix of highly comminuted Footwall material. Overlying this is the Sublayer, the lower part of which contains numerous inclusions, many of them belonging to a suite of ultramafic and mafic rocks (see Naldrett *et al.*, Chapter 11, this volume). The proportion of inclusions tends to decrease upward. The Sublayer is in sharp contact with the overlying Felsic Norite of the Main Mass.

Normally, sulphides are present only in minor amounts (<1%) in the Main Mass norites. They occur throughout the Sublayer, but increase in proportion downward. In some deposits (although not to a great extent at McCreedy West), the proportion is high enough for the lower parts of the Sublayer to constitute ore. The bulk of the ore at the deposit occurs as stringers and disseminations of sulphide in the Footwall Breccia (Breccia ore). Sulphides also occur filling fractures in the mega-breccia adjacent to the Footwall Breccia (Footwall ore) and as Cu-rich veins peripheral to the Footwall ore. At the Strathcona Mine (Coats and Snajdr, Chapter 14, this volume), the Footwall ore has penetrated some 10s of m from the Footwall Breccia and forms an orebody known as the 'Deep Zone'. At Strathcona also, fractures up to 500 m from the contact of the Complex are filled by massive ore consisting dominantly of chalcopyrite.

In general, the Ni and Cu contents and Ni/Cu ratio of the sulphides increase and Co content decreases across the orebody toward the Footwall. Pt, Pd, and Au follow Cu, while Rh, Ru, Ir, and Os follow Co. Coats and Snajdr (Chapter 14, this volume) and Naldrett (Chapter 13, this volume) attribute this to the fractionation of Mss (monosulphide solid solution) from a sulphide liquid, with Ni, Cu, Pt, Pd, and Au becoming enriched in the liquid.

The distribution of ore and its host rocks along the North Range is well explained in terms of the emplacement of a sulphide-bearing Sublayer magma above the Footwall Breccia, followed by settling of the bulk of the sulphide into the porous breccia, and then into open fractures in the underlying Footwall gneisses. As Morris (Chapter 23, this volume) points out, if the North Range is rotated back to its original orientation as indicated by Morris' paleomagnetic data, the ore assumes a position more or less beneath rather than beside the Sublayer, which is consistent with a model calling upon gravitational settling of the sulphides. The overall increase in Cu and its associated elements toward the Footwall indicates that the sulphides were crystallizing and fractionating as they penetrated downward.

SOUTH RANGE DEPOSITS

The Murray Mine is a type example of a South Range

deposit. In many respects it resembles those of the North Range. Footwall rocks are overlain by massive sulphide, which penetrates down into them along fractures. The massive sulphides pass upward into sulphides enclosing mafic and ultramafic inclusions, which, in turn, pass upward into Sublayer containing inclusions and disseminated ore. In contrast to the North Range, the contact between the Sublayer and the overlying Main Mass norite is often gradational, rather than being sharp and well defined.

The main difference between the deposits of the North and South Ranges is the almost complete absence of Footwall Breccia in the latter. The rarity of this breccia is, however, a characteristic of the whole of the South Range in contrast to the North, not just a feature of the ore deposits (Dressler, Chapter 4, this volume). It is suggested that the reason for this is that the South Range represents an environment much closer to the centre of the original Sudbury Structure than the North Range. This is brought out in Figure 25.2, from which it is seen that the present South Range may have been about 8 km from the centre in comparison with 19 km for the North Range.

If the crater was the result of meteorite impact, the floor near the centre can be expected to have been swept clear of debris by the intense, outward moving air wave generated by the explosion. Farther out, debris could have been left behind, protected within troughs and pockets in the floor, and also could have accumulated very rapidly as a result of slumping of the more steeply dipping walls of the crater that occur toward its periphery (Morrison, Chapter 23, this volume). Thus this debris is present as the Footwall Breccia on the North Range, but is not present along the South Range.

OFFSET DIKE DEPOSITS

The Offset Dikes are associated with trough-like embayments in the Footwall. For the most part, the Offset Dikes project out from the embayments along fractures, many of which were previously filled with Sudbury Breccia. It has been shown above that assimilation of breccia material can account for much of the compositional variation of the Quartz Diorite forming the Offset Dikes.

The ore of the Offset Dikes is associated with a distinctive, inclusion-rich facies of the Quartz Diorite. In normal Offset Dike deposits, as typified by those of the Copper Cliff Offset Dike (Cochrane, Chapter 15, this volume) this facies occurs as pipe-like masses with elliptical cross-section and vertical plunge within unmineralized Quartz Diorite. The inclusions of the mineralized facies fall into 2 groups, small (< 2 cm) inclusions consisting of identifiable wall rocks to the dikes, and larger (> 2 cm) inclusions consisting of peridotites, pyroxenites, gabbros, and quartz diorites.

In horizontal plan, distinct breaks, or 'offsets' occur along the Offset Dikes, although the segments separated by the breaks may join up in the third dimension. The impression given by these breaks is that the predominant flow direction of the Sublayer magma was not directly away from the Sudbury Igneous Complex contact, but was at a sharp angle to this (either upward or downward).

Two types of orebodies with distinctive compositions occur within the Copper Cliff Offset Dike. Where the deposits are unrelated to a contact of the dike, sulphides are found concentrated at the centre of the pipes of inclusion-rich Quartz Diorite. The Cu/Ni ratio of the sulphides increases outward from the core of the pipe, which is pyrrhotite rich. Where the deposits are adjacent to a contact, they tend to favour the Footwall, with massive sulphides lying on the Footwall and the intensity of mineralization decreasing upward. In these deposits, the Cu/Ni ratio is higher in the less intense mineralization, increasing upward, although Cu-rich stringers also project downward into the wall rocks of the dike, particularly when this is Sudbury Breccia.

The pipelike nature of the ore deposits suggests to this author (although not to Cochrane) that flow has been in the direction of the pipes, and that these have been injected into an early phase of unmineralized Quartz Diorite.

The dominant ore in both types of deposits consists of rounded blebs of sulphide in Quartz Diorite. Naldrett (1969) suggested that at high pressure in water-rich magma, crystallization of the silicates would be delayed until after that of the sulphides had started, and that this was the explanation for the blebby texture of much of the ore in the Offset Dikes as opposed to the interstitial texture of the ore from other environments. The amphibole-rich nature of the Quartz Diorite is evidence that this was a wet magma. Assimilation of wet Sudbury Breccia matrix would have provided the opportunity for incorporation of much of this water.

Cochrane (Chapter 15, this volume) suggests that upon emplacement, settling of liquid sulphides occurred, either to the Footwall if the pipe was not vertical but was plunging parallel to the lower contact of the dike, or to the lower part of the pipe if it was oriented vertically, thus accounting for the observed distribution of the more massive ore. Crystallization and settling of monosulphide solid solution from this liquid, coupled with the upward displacement of the fractionated, Cu-rich liquid in the case of the contact mineralization, or upward and outward displacement in the case of the vertical pipes, was the explanation for the zoning in these deposits. The fact that the crystallization of silicates was suppressed by the high water content of the magmas allowed easier movement of the

fractionated sulphide liquid. This is the probable explanation of why the fractionated liquid was able to move upward in the contact deposits of this environment, instead of being forced downward and outward into the Footwall as appears to have been the case in the North and South Range deposits.

The orientation of the ore-bearing pipes within the Copper Cliff Offset Dike poses a problem. Morris' data indicate that the South Range Norite has been rotated to the north about its strike direction by approximately 55°. Some of this rotation (23°) is attributed to subsidence at the centre of the Complex during its emplacement and this may not have affected ground as far to the south of the centre as some of the pipes of the Copper Cliff Offset Dike. However, 32° of the rotation is attributed to folding, which presumably should have affected the whole area. This implies that if the Sublayer and Main Mass are contemporaneous, the 120 ore deposit, for example, should have had a plunge (see Cochrane, Chapter 15, this volume, Figures 15.6 and 15.7) of 55° to 60° to the north at the time of its emplacement.

The Frood-Stobie deposit (see Zurbrigg *et al.* 1957; Hawley 1965; Souch, Podolsky *et al.* 1969; and for a brief description, Naldrett, this volume) differs in a number of respects from those of the Copper Cliff Offset Dike. The Frood-Stobie Offset Dike itself is concentrically rather than radially oriented with respect to the Complex. The proportion of sulphide is very much greater, most of the Quartz Diorite constituting ore, and the Quartz Diorite and underlying sulphide pinches and bottoms at depth. The deposit is strongly zoned in a vertical sense, with Cu increasing with respect to Ni, Fe, and Co with increasing depth. Hawley (1965) attributed this 'upside-down' zoning to the cooling of the ore in a reverse thermal gradient, imposed by the hot Complex overlying the Offset Dike. He suggested that the Offset Dike was emplaced downward into a tension fracture that had opened up along a hinge line. The hinge line was associated with a northward rotation of strata lying to the north. Today, this rotation could be interpreted as a result of the subsidence that the author believes to have occurred at the centre of the Complex.

Returning to the orientation of the pipes in the Copper Cliff Offset Dike, if these had an original plunge, and if flow was parallel to their axes as has been argued above, some constraints are placed on the direction in which they flowed. The axes converge with the base of the Complex in an upward direction; this means that either they were emplaced downward, moving toward the centre of the Sudbury Structure, or upward, radiating out from a zone at depth beneath the structure and converging on the base of the Complex. In the opinion of this author, the upward movement is the more likely, although it is contrary to that which

seems to be well established for the Frood-Stobie deposit, which he regards as an exception.

Compositional Variation

The principal minerals of the Sudbury ores are, in order of abundance, pyrrhotite, pentlandite, chalcopyrite, magnetite, and pyrite. Naldrett (Chapter 13, this volume) tabulates numerous other minerals that have been documented in the ores, but they account for a very small proportion of the total.

Although the mineralogy is very uniform, the proportions of the minerals show marked variation, both within and between different deposits. This is reflected in variation in the Ni and Cu content of the sulphides. Within deposit variation, in which Ni, Cu, Cu/Ni, Pt, Pd, and Au increase together (toward the Footwall in the case of the contact deposits) has been discussed above and is documented for the Strathcona and Levack West deposits in Table 25.6. Between-deposit variation on the North Range is described by Coats and Snajdr (Chapter 14, this volume) who report that in the Strathcona embayment, the Ni content of sulphides of the deposits decreases systematically eastward from the Fraser Deep deposit at the lowest point of the embayment to the Longvack deposit. This decrease is accompanied by an increase in the Cu/(Cu + Ni) ratio. West of the Fecunis Lake Fault, there is a less pronounced and less systematic decrease in the Ni content of sulphides and increase in Cu/(Cu + Ni) ratio westward to the Hardy deposit. An impression of the magnitude and nature of the compositional variation can be obtained by comparing the estimates of the overall composition of the McCreedy West deposit, corresponding to a deposit with a high Ni in sulphide content, to that for the Strathcona deposit, with a low Ni in sulphide content, as given in Table 25.6.

Naldrett *et al.* (1982) concluded that 2 main factors have influenced the compositional variation. One is the fractional crystallization of monosulphide ($\text{Fe}_{1-x}\text{S}-\text{Ni}_{1-x}\text{S}$) solid solution (Mss) from a sulphide liquid, and the other is the progressive segregation of a sulphide liquid from a silicate magma.

Variations in composition resulting from fractional crystallization of Mss will be dependent on the relative partitioning of different elements between liquid sulphide and Mss. Ni, Cu, and Pd are known to favour the liquid, Cu to a greater degree than Ni, while Co, Rh, and Ru are known to favour Mss (Craig and Kullerud 1969; Distler *et al.* 1977). Because of their chemical similarities, it can be predicted that Pt will follow Pd, and Ir and Os will follow Ru. Thus, the progressive fractionation should result in an increase in the concentrations of Cu, Ni, Pt, and Pd, and an increase in the Cu/(Cu + Ni), Cu/Co, and (Pt + Pd)/(Ru + Ir + Os) ratios in the liquid.

TABLE 25.6: COMPOSITIONAL DATA ON SOME SUDBURY ORES.

	Ore Types within Deposits						Overall Estimates for Deposits												
	Hanging		Footwall		Footwall		Cu Stringers McC.	Cu' Zone Strath.	Deep Cu'		Strath- cona	McCreedy West	Little ^a		Falcon- bridge	810	830	Copper Cliffs	
	Strath.	McC.	Strath.	McC.	Strath.	McC.			Strath.	Strath.			No.1	No.2				865	900
Ni ^a	3.1	3.4	5.6	4.0	5.8	5.8	2.6	0.39	1.72	3.6	5.7	5.7	3.6	3.4	5.4	6.1	6.1	6.1	4.3
Cu ^a	0.37	1.2	3.3	2.3	5.3	5.3	27.8	29.6	2.47	2.8 ²	3.7	3.7	4.5	4.5	1.5	6.3	6.3	7.0	4.6
Cu/(Cu + Ni)	0.11	0.26	0.37	0.36	0.48	0.48	0.91	0.99	0.94	0.44	0.39	0.39	0.56	0.57	0.22	0.51	0.51	0.53	0.39
Pt ³	114	413	1098	750	1334	1334	3370	2551	4910	420	1154	2024	3007	3007	550				
Pd ³	105	380	1223	701	1350	1350	5948	890	6970	372	1253	2174	4573	4573	380				
Rh ³	60	20	228	16	53	53	<10	4		30	186	119	303	303	290				
(Ru + Ir + Os) ⁷	101	23	161	11	49	49	<5.3	5.2		41	129	213	406	406	410				
(PtPd)	2.2	34	14	132	54	>1758	662			19	19	19	19	19	2.3	10	8.3	12.5	3.3
(Ru + Ir + Os) Cu/Co																			
TotPGE/ (Ni + Cu)	1.8	8.6	19	18	48	48	1030	1430	493	493	23	23	23	21	6.8	35	32	32	22
	11x10 ⁻⁶	18x10 ⁻⁶	30x10 ⁻⁶	23x10 ⁻⁶	25x10 ⁻⁶	25x10 ⁻⁶	31x10 ⁻⁶	11.5x10 ⁻⁶	45x10 ⁻⁶	13x10 ⁻⁶	29x10 ⁻⁶	29x10 ⁻⁶	53x10 ⁻⁶	105x10 ⁻⁶	24x10 ⁻⁶				12

1. Data from Naldrett *et al.* (1982) except as indicated.

2. This Cu content for Strathcona has been obtained by taking the Cu/Ni ratio as expressed in the ore reserves for the deposit and multiplying this by the Ni content of the sulphides i.e. 3.6 wt. % Ni.

3. Data from Coats and Snajdr (Chapter 14, this volume) except that for Rh, Ru, Ir, and Os which are from a single sample reported by Naldrett *et al.* (1982).4. Data on Ni, Cu, Co, Pt and Pd from Davis *et al.* (Chapter 16, this volume), that on Rh, Ru, Ir, Os from Naldrett (1981).

5. Data from Cochrane (Chapter 15, this volume).

6. Expressed as Wt. percent metal in 100 percent sulphides.

7. Expressed as ppb metal in 100 percent sulphides.

The variations between different ore types at both Strathcona and McCreedy West on passing from hanging wall to Footwall are regarded as the consequence of progressive fractionation. From Table 25.6, it is seen that systematic changes of the kind predicted above occur within the data. The $\text{Cu}/(\text{Cu} + \text{Ni})$ and $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ ratios appear to be particularly reliable indices of the compositional changes resulting from fractionation. These 2 parameters have been used to construct Figure 25.10, in which the lines connecting the different ore types from a single deposit indicate the kind of compositional change to be expected as a result of Mss fractionation.

Data on the partitioning of elements between co-existing sulphide and silicate melts are sparse, but those available indicate that values of the partition coefficient D_M/L (= concentration in wt % of metal M in sulphide liquid/concentration of M in silicate liquid) for Ni and Cu are similar and around 250; that for Co is lower and around 80; and those for all of the PGE are very high, being over 1000 and perhaps approaching 100,000 (see Rajamani and Naldrett 1978; Boctor and Yoder 1983; Campbell and Barnes 1984). Thus, the progressive removal of a sulphide liquid from a silicate melt would be expected to deplete all of these elements in the melt; however, this effect should be less marked for Co and very much more marked for the PGE than for Ni and Cu. Consequently, in comparison with an early segregate from a given silicate melt, a late segregate should have lower overall concentrations of these elements, similar $\text{Cu}/(\text{Cu} + \text{Ni})$ and $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ ratios, and lower Cu/Co and $\text{PGE}/(\text{Cu} + \text{Ni})$ ratios.

The progressive eastward decrease in Ni sulphides reported by Coats and Snajdr (Chapter 14, this volume) as characterizing deposits associated with the Strathcona embayment can be interpreted as the consequence of a magma moving along this embayment from west to east, segregating the sulphides of each of the ore deposits in turn, and becoming progressively more depleted in the process. If one uses McCreedy West as an example of a deposit segregating from some of the less depleted magma characteristic of the area to the west, a comparison of this with the Strathcona Mine indicates that the $\text{Cu}/(\text{Cu} + \text{Ni})$ and $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ ratios are similar in the 2 deposits; that the Strathcona Mine has lower metal contents than McCreedy West; and that the $\text{PGE}/(\text{Cu} + \text{Ni})$ ratio of the Strathcona Mine is very much lower. These observations agree with the predictions and lend support to the hypothesis that the broad regional variations in metal contents and ratios that are observed at Sudbury are due to the progressive depletion of host magmas as a result of the segregation of sulphide.

Since the $\text{Cu}/(\text{Cu} + \text{Ni})$ and $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ ratios should not be overly sensitive to the fractional segregation of sulphide, the diagram

constructed using these 2 parameters (Figure 25.10) should provide information about some of the other processes affecting the composition of sulphide ores, unobscured by the segregation of differing proportions of sulphide. Variations resulting from the fractionation of Mss have already been discussed. Deposits segregating from initially similar magmas should plot in the same place; it is seen that Strathcona and McCreedy West do so. Little Stobie deposits Number 1 and Number 2 also plot together, although they have higher $\text{Cu}/(\text{Cu} + \text{Ni})$ ratios than McCreedy West and Strathcona. It is possible that this is the consequence of the fractionation of olivine from the magma hosting them, which would lower the Ni content without affecting the Cu or PGE contents greatly. The Copper Cliff Offset Dike deposits 810, 830, and 865 plot fairly close together, although with a somewhat lower $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ ratio than the others. It is suggested by this author that the area occupied by all of the deposits that have been discussed up to this point represents the 'norm' for Sudbury.

The Falconbridge deposit is clearly an exception to the postulated 'norm', having much lower values of both ratios, and resembling the product of the earliest fractionation (the Hanging Wall ore) at Strathcona.

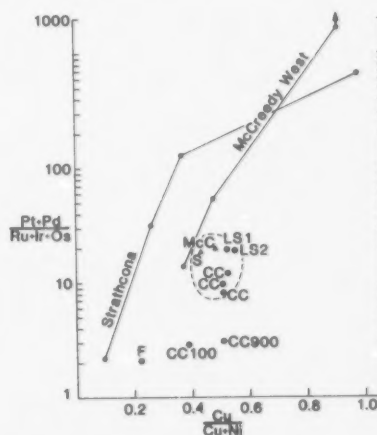


Figure 25.10. Plot of $(\text{Pt} + \text{Pd})/(\text{Ru} + \text{Ir} + \text{Os})$ vs $\text{Cu}/(\text{Cu} + \text{Ni})$ for several Sudbury ore deposits. The points connected by straight lines indicate compositional changes that are believed to result from fractional crystallization of Mss from a sulphide melt. Average compositions of many deposits are rather similar and fall within the oval. Some deposits are distinctly atypical and plot well below the circle. In the case of Falconbridge, it is believed that a significant proportion of fractionated ore is missing from the deposit.

KEY

- F = Falconbridge #5 shaft
- CC, 100, 900 = Copper Cliff
- McC = McCreedy West
- S = Strathcona
- LS1, LS2 = Little Stobie Numbers 1 and 2

Naldrett *et al.* (1982) pointed this out, arguing that the present Falconbridge deposit represented the early crystallization products of a much larger orebody, of which the part rich in Cu, Pt, and Pd had been faulted away, and either had been removed by erosion, or remained to be discovered. The Copper Cliff Offset Dike deposits 100 and 900 also stand out as anomalous. It is possible that they also represent early crystallizing fractions and that ore richer in Pt and Pd than that sampled either remains to be sampled, or originally occupied a part of each of these shoots that has been removed by erosion.

Origin of the Ore

Although there is considerable variation in the characteristics of different ore deposits, there are a number of features common to all of them. These include:

1. Embayments or other irregularities at the base of the Sudbury Igneous Complex. An increase in sulphide content is usually observed at the lower contact throughout the Complex, but it is where irregularities exist that the zone of sulphide thickens and increases in proportion of sulphide sufficiently to form ore.
2. The presence of Sublayer. The spatial relationship of ore to this rock type is such that the sulphides appear to have settled out of bodies of Sublayer. Sulphides also occur within Quartz-rich and Mafic Norites, but except where they have been removed from their original position by faulting, orebodies are invariably associated with Sublayer.
3. Ultramafic inclusions within Sublayer. Some Sublayer is mineralized, other varieties seem to be devoid of significant sulphide. There is little to distinguish mineralized from unmineralized Sublayer in so far as texture, mineralogy, and chemical composition are concerned, except for the obvious presence of sulphide. All types of Sublayer contain inclusions, but both in the contact and the offset dike environments, the mineralization is associated only with Sublayer that carries members of a suite of mafic and ultramafic inclusions that Scribbs *et al.* (1984) and Naldrett *et al.* (Chapter 11, this volume) conclude are derived from one or more layered intrusions.

RELATIONSHIP BETWEEN INCLUSIONS, SUBLAYER, AND MAIN MASS OF THE SUDBURY IGNEOUS COMPLEX

As discussed above, the REE profiles of the Sudbury rocks differ from those of most layered intrusions and suggest that contamination by country rocks has occurred on a large scale. The similarity in the profiles of

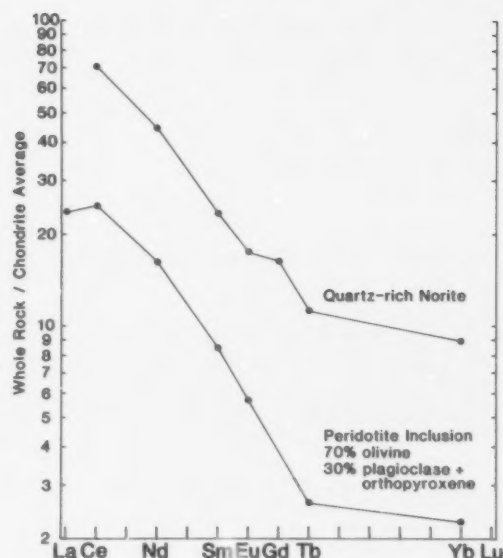


Figure 25.11. REE profile for a harzburgite inclusion in the Sublayer compared with that for other Sudbury Igneous Complex rocks (B.V. Rao, personal communications, 1984).

the Sublayer and the Main Mass rocks is suggestive that the magmas responsible for them have a common heritage. The limited data available for mafic and ultramafic inclusions in the Sublayer (Figure 25.11 and Kuo 1976) indicate that these have REE profiles of similar slope to the Main Mass although of lower overall abundance. Thus, there is some evidence that the inclusions were derived from a magma that had suffered contamination similar to that affecting the remainder of the Sudbury Igneous Complex rocks.

The MgNos of samples of Main Mass and Sublayer are illustrated in Figure 25.12 (contrary to the previous representation of MgNos, in this Figure only 90% of the total Fe has been included in calculating them, to allow for Fe in the magma in the ferric state). Using Roeder and Emslie's (1970) relationship between the Mg/Fe ratio of olivine and of the basaltic liquid that is in equilibrium with it, MgNos of liquids in equilibrium with the olivine of the inclusions have been calculated. It can be seen that they span the same range of MgNos as exhibited by the Sublayer samples. This indicates that, ignoring the SiO₂ contents of all of the magmas, the range of olivine compositions observed in the inclusions is precisely what would be expected in cumulus rocks crystallizing from a magma evolving along a compositional trend such as that recorded within the Sublayer. Returning to the question of the SiO₂ content of the Sudbury magmas, although olivine has not been described in the literature as being a common constituent of the Sublayer matrix, Pattison (1979) has reported it as present at Whistle, and G.A. Morrison (Staff Geologist, Inco Limited, Sudbury, personal communication, 1984) has stated that it is

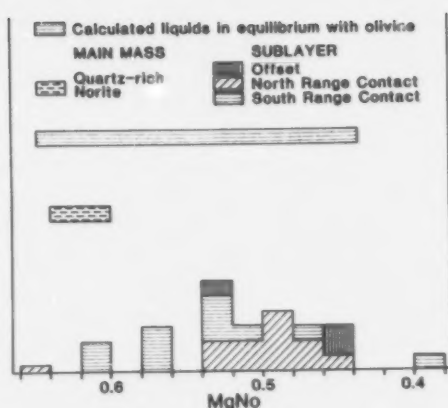


Figure 25.12. MgNos of Main Mass and Sublayer samples that are believed to approximate the compositions of liquids, compared with the calculated MgNos of liquids in equilibrium with olivines of the inclusions of the Sublayer.

known to exist at a number of other localities. Olivine-bearing Sublayer here is not obviously different in composition to that devoid of olivine, which suggests that olivine may have played a role in the fractionation of much of the Sublayer, and only has disappeared from the liquidus at about the stage at which it was emplaced.

The 2 lines of evidence, REE profiles, and olivine compositions lead this author to suggest that inclusions, Sublayer, and Main Mass norite are all related, and to propose the model given at the end of this chapter.

SEGREGATION OF SULPHIDES

The Sudbury Igneous Complex differs from other layered complexes in a number of significant ways, including:

1. evidence that the area into which it was intruded had been involved in a catastrophic explosion, in the view of this author, probably the consequence of the impact of a meteorite
2. the rocks of the Complex are very siliceous when compared with other intrusions on the basis of the $Mg/(Mg+Fe)$ ratios of their pyroxenes (see Naldrett and Hewins, Chapter 10, this volume, Figures 10.5 and 10.6) implying that the magma responsible was unusually siliceous for its state of fractionation
3. other compositional data based on major and trace elements and isotopic analyses that indicate that the high SiO_2 content is the consequence of country rock assimilation
4. an unusually large number of occurrences of very concentrated sulphide³

Irvine (1975) pointed out that assimilation of

SiO_2 -rich material by a mafic magma could lower the solubility of sulphur within it, and suggested that this had occurred at Sudbury. The principle is illustrated in highly simplified form in the isothermal section of the $FeO-FeS-SiO_2$ system in Figure 25.13. Composition A lies in the field of homogeneous liquid, but addition of SiO_2 to change its composition to B moves it into a 2-liquid field and will result in the segregation of 2 immiscible liquids, one silicate-rich (Y) and the other sulphide-rich (X). The evidence bearing on the SiO_2 -rich nature of the Sudbury Igneous Complex lends support to this hypothesis. The evidence indicating that

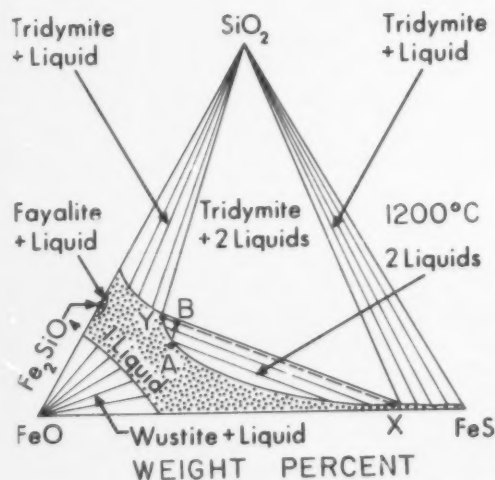


Figure 25.13. 1200°C isotherm of the $Fe-S-O$ system illustrating how the addition of SiO_2 to a homogeneous, sulphide-rich liquid of composition A will change its composition to point B, where it will consist of 2 liquids, one silicate-rich (Y) and the other sulphide-rich (X).

³Surprisingly, the Sudbury Igneous Complex is not unusually rich in sulphide. If the amount of sulphide present in the past production plus published reserves of all known ore deposits down to a depth of 1600 m is calculated; and if this number is multiplied by 5 (a number to account for the sulphide in ore deposits still to be discovered, and in those sulphide concentrations that are not economic—it is probably very generous); and if this same density of ore deposits is assumed to occupy all of the contact of the Complex down to a depth of 9 km, which is the depth obtained if the surface dips of the contacts are projected down until they intersect; the S in all of the sulphides estimated in this way will raise the concentration of sulphur in the volume of the Complex obtained in this manner by 120 ppm. Duke and Naldrett (1976) have found that the average S content of the Main Mass norites is about 450 ppm. Thus, combining this with the additional figure estimated to be the maximum concentrated in the ore deposits, one still obtains a concentration that is about one half of that that could be dissolved by a basaltic magma saturated in sulphide.

extensive country rock assimilation has occurred points to how the SiO_2 -rich composition has been achieved. The highly fractured ground underlying an explosion site, coupled with the heating and melting resulting from the explosion would have provided the ideal environment in which country rock assimilation could have occurred.

A MODEL FOR THE SUDBURY IGNEOUS COMPLEX

It is suggested that the catastrophic explosion that occurred in the Sudbury region 1.85 Ga ago gave rise to the Onaping Formation, fractured the underlying crust, and triggered ascent of a magma similar in its initial composition to continental flood basalt (this author believes that the weight of available evidence points to the impact by an extra-terrestrial body as the cause, although impact is not essential to the develop-

ment of this model). Magma probably rose through a centralized plumbing system in the lower crust, but some of it spread out through numerous subsidiary channels as it entered the highly fractured ground beneath the crater (Figure 25.14). It is possible that these hidden, flanking intrusions account in part for the buried mass of mafic and ultramafic rock that the analysis of gravity and magnetic data by Gupta *et al.* (Chapter 18, this volume) has indicated underlies and extends beyond the present Sudbury Structure.

On its initial ascent, the magma fractionated to some degree, achieving a MgNo of about 0.65 or slightly less. Batches of magma that infiltrated flanking subsidiary channels cooled, became contaminated through reaction with their surroundings, and fractionated further, giving rise to olivine- and pyroxene-rich cumulates. The contamination, coupled with the cooling, caused sulphides to precipitate at an early stage; these collected as massive bodies beneath the cumulates in the flanking chambers of the plumbing system. The main body of magma lost heat less quickly than that in the flanking chambers, and thus fractionated less rapidly; because it cooled more slowly, it reacted with country rocks to an even greater extent than was the case in the flanking bodies.

Repeated subsidence at the centre of the Sudbury Structure was accompanied by successive injections of magma along the unconformity between the crater floor and the overlying, relatively unconsolidated, and thus low density Onaping Formation. The Mafic Norite of the North Range probably represents an early injection of the main body of magma, at a slightly earlier stage in its fractionation and before it became as highly contaminated as the magma that gave rise to the subsequent main injection.

The faster cooling, and thus more fractionated (consistent with the MgNos) but less contaminated (consistent with the Sr initial ratios) magma of the flanking bodies was also squeezed up to intersect the crater floor, where it spread out, exploiting 'troughs' and 'embayments' in the floor filled with Footwall Breccia and also infiltrating fractures in the basement rocks to form the Offset Dikes. This magma is thus responsible for the Sublayer. In some instances (Figure 25.14), as it rose up through the basement, it intersected and disrupted overlying bodies, picking up sulphides and ultramafic cumulates in the process, thus accounting for the association between the mineralization and the xenoliths. Other batches of magma did not intersect overlying bodies and were emplaced carrying only country rock inclusions and giving rise to the unmineralized Sublayer that has been described. The fact that the Sublayer intrusions were derived from a number of bodies following parallel, but distinct, evolutionary trends accounts for the greater variability of the Sublayer in MgNo and Sr initial ratio in comparison with the Main Mass.

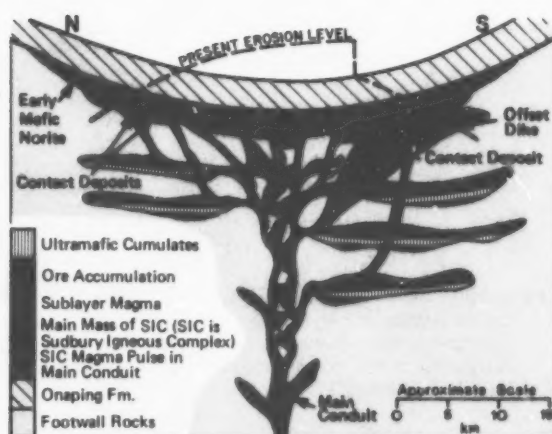


Figure 25.14. Schematic cross-section illustrating the emplacement of the Sudbury Igneous Complex. Magma rises up a vertical conduit into a highly fractured zone beneath an explosion (possibly impact) crater. The central body of magma cools somewhat slowly, assimilating much of the fractured country rocks. Subsequently, it is emplaced into the crater, beneath the low density Onaping Formation, in response to structural readjustments in the area. It is probable that this is a multi-stage process. Magma has also spread out as a series of sills peripheral to the central conduit. Assimilation also occurs within these, although possibly to a lesser extent than in the central conduit due to their cooling more rapidly. The magma of the sills deposits sulphide and fractionates giving rise to olivine- and pyroxene-rich cumulates. Fractionated magma from the flanking sills also works its way up to the crater floor, intruding to form the Sublayer of the contact and offset dikes. Where magma from a lower sill has cut and disrupted an overlying one, it has picked up sulphides and inclusions, intruding with these in suspension within itself. Subsequently, both sulphides and inclusions settle out to give rise to the ore deposits with their typical zonation of massive sulphides overlain by inclusion-bearing massive sulphide overlain in turn by sulphide-rich Sublayer rock.

Some Offset Dike deposits such as the Frood-Stobie deposit, appear to have been injected from above. It has been commonly thought that the majority were emplaced either in this manner, or laterally, outward from the contact of the Sudbury Igneous Complex. As discussed above, this gives rise to the question of the orientation of the mineralized pipes in the Copper Cliff Offset Dike, which, after correction for subsequent rotation as documented paleomagnetically, appear to have been plunging at 40° to 60° toward the Complex at the time of their emplacement. This is not unreasonable in the light of the reconstruction of Figure 25.14, although this brings the implication that some of the dikes were injected from below, not laterally or from above.

This model shows successive waves of magma being introduced from below in response to subsidence of the Complex, and that the Main Mass and Sub-layer magmas existed at the same time, but in different places, and thus can explain the conflicting age relationships between the 2 which have been reported in the literature for so long.

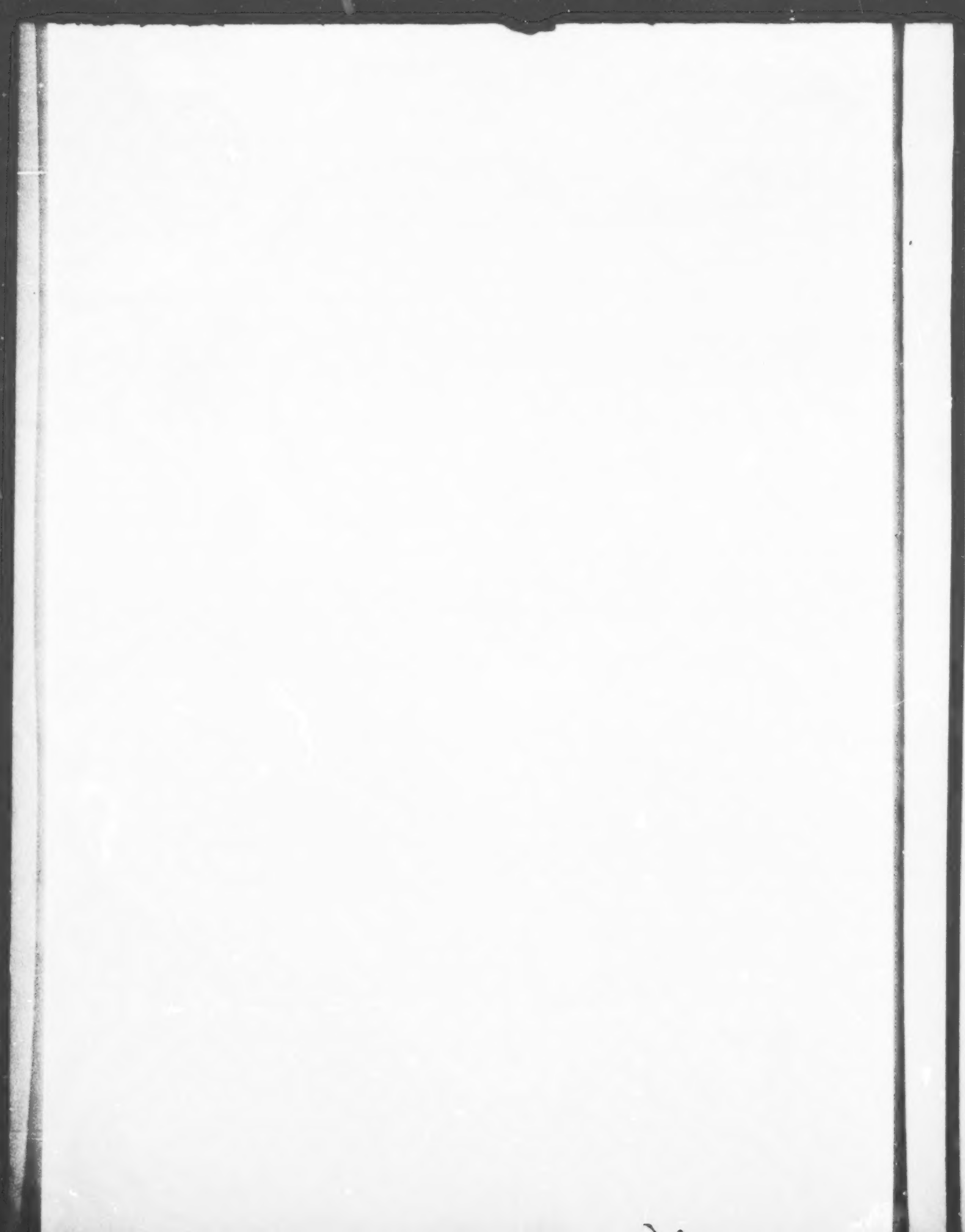
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Glossary of Sudbury Geology Terms

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INTRODUCTION

The literature on Sudbury geology is replete with a large number of terms that have been applied to certain rock types. In some cases, a single rock type has been given two or more names, and in others, a single name has been applied to 2 or more different rock types. The profusion of names reflects both the complexities of Sudbury geology and the evolution of scientific knowledge and terminology.

The terms listed and defined in this glossary were agreed upon by the industry, university, and government geoscientists who are authors in this volume. In the interest of clarity, it has been found desirable to introduce some new terms and to redefine certain older terms.

Terms from the literature of the last quarter-century which are not used in the present volume, or which are used in a different sense, are given in the List of Previously Used Terms together with the current equivalents.

GLOSSARY

Basin: see Sudbury Basin.

blebby disseminated sulphide: an ore type, characterized by small, rounded to elliptical blebs of sulphide in a silicate matrix.

blebby silicates in sulphide: an ore type, characterized by the presence of small, rounded to elliptical and club-shaped inclusions of fine-grained quartz diorite in a matrix of sulphide minerals.

Complex: see Sudbury Igneous Complex.

contorted schist inclusion sulphide: an ore type, characterized by contorted fragments of schist and/or inclusions of quartz.

East Range: a portion of the Sudbury Igneous Complex, commonly considered as an integral part of the North Range, with which it is geologically similar. It extends from the pronounced flexure of the Complex in Norman Township southward to the faulted flexure in Falconbridge Township.

felsic norite: the major unit of the Lower Zone of the Sudbury Igneous Complex in the North Range.

Footwall Breccia: a collective term for various breccias found in the Footwall of the Sudbury Igneous Complex, particularly on the North Range. Many textural and compositional variants can be defined locally. The breccia is characterized by abundant Footwall rock fragments, and locally by sulphide inclusions, in a contact-metamorphic matrix consisting mainly of highly variable proportions of plagioclase, quartz, pyroxene, amphibole, biotite, and granophyric intergrowth of feldspar and quartz. Sulphide may or may not be present in the matrix. The breccia comprises a major portion of the ore deposits on the North Range.

fragmental and disseminated sulphide: an ore type, characterized by the presence of subangular fragments of sulphide which comprise part of the fragment population of the host rock, and by the presence of small blebs of disseminated sulphide.

gabbro-peridotite inclusion sulphide: an ore type, characterized by inclusions of mafic and ultramafic rocks in an abundant matrix of sulphide and minor noritic rocks.

granophyre: the major unit of the Upper Zone of the Sudbury Igneous Complex.

inclusion-bearing massive sulphide: an ore type, characterized by the presence of angular fragments of Footwall rocks in massive sulphide.

interstitial sulphide: an ore type characterized by sulphides which fill interstices between euhedral plagioclase and pyroxene.

Levack Gneiss Complex: a belt of mainly high-rank metamorphic gneisses adjacent to parts of the North Range of the Sudbury Igneous Complex.

Lower Zone: the lower, noritic portion of the Main Mass of the Sudbury Igneous Complex. In the North Range, it consists of the felsic norite and mafic norite; in the South Range, it consists of South Range norite and quartz-rich norite.

mafic norite: the basal unit of the Main Mass of the Sudbury Igneous Complex in the North Range.

Main Mass: the major part of the Sudbury Igneous Complex, consisting of the Lower, Middle, and Upper Zones, and exclusive of the Sublayer.

massive sulphide: an ore type, consisting almost entirely of sulphide minerals.

GLOSSARY

Middle Zone: the central portion of the Main Mass of the Sudbury Igneous Complex consisting mainly of quartz gabbro.

North Range: the northern portion of the Sudbury Igneous Complex. It is separated from the southern portion by a zone of faulting, extending from the Chicago Fault to the Cameron Creek Fault, at the western end of the Complex. Its eastern end is the pronounced faulted flexure in Falconbridge Township. The East Range is commonly considered as an integral part of the North Range.

offset; offset dike: a radial or concentric dike of the Sudbury Igneous Complex, in general, consisting predominantly of quartz diorite of the Sublayer but may include significant proportions of Footwall Breccia material.

plagioclase-rich granophyre: a unit of the Upper Zone of the Sudbury Igneous Complex.

quartz diorite: a variety of the Sublayer of the Sudbury Igneous Complex.

quartz gabbro: a unit of the Sudbury Igneous Complex comprising the Middle Zone.

quartz-rich norite: the basal unit of the Lower Zone of the Sudbury Igneous Complex in the South Range.

ragged disseminated sulphide: an ore type, characterized by small, closely packed inclusions in a scanty matrix consisting of sulphide and subordinate noritic rock. The inclusions are mainly gabbroic, and the sulphide occurs as crescentic or cusp-like masses partly filling interfragment spaces.

South Range: the southern portion of the Sudbury Igneous Complex, lying south of the zone of faulting between the Cameron Creek and Chicago Faults at the western end and south of the pronounced faulted flexure at the eastern end in Falconbridge Township.

South Range Norite: the upper unit of the Lower Zone of the Sudbury Igneous Complex in the South Range.

stringer sulphide: an ore type in which sulphide minerals occur in relatively narrow veins.

Sublayer: a unit of the Sudbury Igneous Complex. Two varieties, Contact Sublayer and Offset Sublayer, are recognized. See below.

Contact Sublayer: the lowermost unit of the Sudbury Igneous Complex. It is characterized by its discontinuous and inhomogeneous nature, by the presence of 2 distinct types of inclusions set in an igneous matrix, and by the presence of sulphides in varying amounts. The inclusions consist of footwall rock types and/or a group of mafic to ultramafic rocks.

Offset Sublayer: the varieties of Sublayer which occupy the offset dikes of the Sudbury Igneous Complex. The predominant variety is quartz diorite which may be inclusion and sulphide-free or may contain 2 distinct inclusion types and sulphides as in Contact Sublayer.

Sudbury Basin: the area enclosed by the Sudbury Igneous Complex and occupied by rocks of the White-water Group.

Sudbury Breccia: pseudotachylite consisting dominantly of locally derived, commonly rounded, rock fragments in a fine-grained, generally dark-coloured matrix that consists of comminuted rock and mineral fragments. In a few places, recrystallized melt matrices have been observed.

Sudbury Igneous Complex: a large differentiated layered intrusion with which the nickel-copper-precious metals deposits of the Sudbury district are associated. The Complex is sub-divided into a Main Mass (consisting of Lower, Middle, and Upper Zones) and a Sublayer unit.

Sudbury Event: the event (or events) leading to formation of the Sudbury Structure.

Sudbury Structure: a collective term of a feature consisting of 3 main elements:

- (1) the Sudbury Igneous Complex
- (2) the Sudbury Basin
- (3) the brecciated country rocks of the Superior and Southern Provinces which surround the Complex.

Upper Zone: the uppermost portion of the Sudbury Igneous Complex, consisting of the granophyre and plagioclase-rich granophyre units.

List of Previously Used Terms

<i>Previously Used Term</i>	<i>Current Term</i>
basic norite	Contact Sublayer
biotite norite	mafic norite
biotitic-type norite	mafic norite
black norite	1. mafic norite on the North Range 2. relatively unaltered South Range norite
brown norite	relatively unaltered South Range norite
coarse norite	felsic norite
common Sudbury breccia	Sudbury Breccia
contact breccia	intermingled Contact Sublayer and Footwall Breccia in North Range area
dark norite	mafic norite
dark norite breccia	Contact Sublayer
feldspathic gneiss complex	Levack Gneiss Complex
femic norite	mafic norite
granite breccia	Footwall Breccia
granophytic micropegmatite	granophyre
gray norite	usage uncertain, appears to have been used for mafic norite and for Contact Sublayer
green norite	altered phase of the South Range norite
grey breccia	Footwall Breccia
grey norite	felsic norite
hanging-wall breccia	Contact Sublayer
immiscible silicates in sulphide	blebby silicates in sulphide
igneous sublayer	Contact Sublayer
inclusion norite	Contact Sublayer
inclusion basic norite	Contact Sublayer
inclusion quartz norite	a phase of Offset Sublayer
Irruptive	Sudbury Igneous Complex
late granitic breccia	Footwall Breccia
leucocratic breccia	Footwall Breccia
leucocratic norite	felsic norite
leucocratic sublayer breccia	Footwall Breccia
Levack breccia	Sudbury Breccia
lineated gray norite	mafic norite
mafic norite	original usage for Contact Sublayer, recent usage exclusively for mafic norite
melanocratic norite	mafic norite
micropegmatite	granophyre and plagioclase-rich granophyre comprising the Upper Zone of the Sudbury Igneous Complex
Nickel Irruptive	Sudbury Igneous Complex

GLOSSARY

List of Previously Used Terms

<i>Previously Used Term</i>	<i>Current Term</i>
norite	the rock type comprising the Lower Zone of the Sudbury Igneous Complex. Varieties recognized in this volume are felsic norite, mafic norite, quartz-rich norite, and South Range norite. Many varietal terms have been used in earlier literature (e.g. basic norite). Most such terms refer to norite of the Lower Zone, a few refer to Contact Sublayer. Since 1957, the following additional terms have been used, predominantly in the literature, with a few being used locally in industry: basic, biotite, biotitic-type, black, brown, coarse, dark, dark norite breccia, felsic, femic, gray, green, grey; inclusion; inclusion basic; leucocratic; lineated gray, mafic, melanocratic, north rim-type, poikilitic, quartz, quartz dioritic-type, salic, sublayer, xenolithic
north rim-type norite	felsic norite
oxide-rich gabbro	Middle Zone of Sudbury Igneous Complex in the North and East Ranges
plagioclase-rich rock	plagioclase-rich granophyre
poikilitic norite	mafic norite
quartz diorite	most recent usage has been for Offset Sublayer; less recently and less commonly for Contact Sublayer, for both, and rarely, for mafic norite
quartz diorite breccia	Sublayer
quartz diorite-type norite	mafic norite
quartz norite	a variety of felsic norite in the North Range
salic norite	felsic norite
sublayer norite	Contact Sublayer
Sudbury Irruptive	Sudbury Igneous Complex
Sudbury Nickel Irruptive	Sudbury Igneous Complex
transition zone	Middle Zone of the Sudbury Igneous Complex
upper gabbro	Middle Zone of the Sudbury Igneous Complex in the South Range
xenolithic norite	Contact Sublayer

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